CHALMERS
UNIVERSITY OF TECHNOLOGY

Synergies between Renewable Energy and Water Management Systems

A Systems Perspective on Resilient Irrigation in Rwanda

Master's thesis in Sustainable Energy Systems

Nathalie Pettersson

DEPARTMENT OF ELECTRICAL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

Master's thesis 2025

Synergies between Renewable Energy and Water Management Systems

A Systems Perspective on Resilient Irrigation in Rwanda

NATHALIE PETTERSSON

Department of Electrical Engineering
Division of Electric Power Engineering
Chalmers University of Technology
Gothenburg, Sweden 2025

Synergies between Renewable Energy and Water Management Systems
A systems Perspective on Resilient Irrigation in Rwanda
NATHALIE PETTERSSON

Supervisor and Examiner: Jimmy Ehnberg, Department of Electrical Engineering

Master's Thesis 2025
Department of Electrical Engineering
Division of Electric Power Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 10 00

Cover: Water spraying from a hose with small holes, irrigation farmland in eastern Rwanda

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2025

Synergies between Renewable Energy and Water Management Systems
A systems Perspective on Resilient Irrigation in Rwanda
NATHALIE PETTERSSON
Department of Electrical Engineering
Chalmers University of Technology

Abstract

Water, energy and food systems are essential for human development and modern life but face growing, complex and overlapping challenges under climate change. This thesis examines these issues in a case study in eastern Rwanda, focusing on irrigation and water purification under climate change. A linear optimisation model was developed that sized and determined operation for cost-effective electrified irrigation systems using two different set-ups. One set-up combined solar photovoltaics and bio-diesel generators. The other set-up used only solar energy. Both met energy demand sustainably but the bio-diesel system was more cost-effective and flexible. The results showed that slightly oversizing the system enabled water purification at lower cost than separate sizing of each system. Climate change modelling cases revealed cost increases of up to 6% for irrigation alone and 23% when combined with purification. This highlights the need for strategic resilience planning. Furthermore, prioritisation strategies strongly influenced system performance when not adapted to climate change. The findings highlight that sustainable electrified irrigation is achievable. Although integrated designs and careful trade-off navigation in the Water-Energy-Food Nexus remain critical under climate uncertainty, broader challenges, including infrastructure, materials, and political factors pose other pressures regarding these systems.

Keywords: Renewable Energy Systems, Linear Optimization, Irrigation, Off-grid, Water Purification, Climate Change

Acknowledgements

This thesis would not have been possible without the opportunity to conduct a field study in Rwanda, an experience that shaped both the project and my understanding in profound ways. I would like to begin by expressing my sincere thanks to my supervisor, Jimmy Ehnberg, for his support, guidance, and help from the very start. I am deeply grateful to Pierre Damien Uwitije, without whom the village of Tabagwe, the focus of the case study in this thesis, would have remained unknown to me. Thanks also to Associate Professor JMV Bikorimana for his valuable advice and help in facilitating important contacts. I sincerely thank Consolee Mukeshimana Kirenga for her vital translation support, which greatly enriched my understanding of life outside Kigali, and Francois-Xavier Ndekezi, whose expertise in water distribution provided many new insights. I am also thankful to the people of Tabagwe for their generosity and openness, which made this study possible.

This Master's thesis was undertaken within the Strategic Partnership between the University of Rwanda and Chalmers University of Technology. I thank the staff and students at the UnIPOD Rwanda for hosting and providing me with support during my visit to Rwanda. I extend my thanks to the University of Rwanda for welcoming me.

I am thankful to the Global Mentorship Program and to Kristina Henricsson Briggs, who administers the scholarship, as well as to Fredrik Eliesson, my mentor from the program, for his valuable guidance. I also gratefully acknowledge the Åforsk Travel Grant and the K G Hallby Fund for their scholarships. The combined support from these scholarships made the field study and research trip to Rwanda possible. I also thank the Trans-African Hydro-Meteorological Observatory (TAHMO) for providing meteorological data used in this research.

Finally, a heartfelt thanks to my friends Amelia and Alida, the trip to Rwanda would not have been the same without you, and to my fiancé, Rasmus, for all his love and support throughout this project.

Nathalie Pettersson, Gothenburg, June 2025

Contents

1

Introduction

Today, humanity faces several complex and interconnected challenges that require holistic and interdisciplinary approaches in the search for resilient solutions. Among these, climate change represents a significant threat to both natural systems and human civilisations. Its impact is especially critical within the Water-Energy-Food Nexus, where essential resources are closely interconnected and face increasing pressure. Notably, those most affected by climate change are often the least responsible for the emissions driving it. Many developing countries, particularly in Sub-Saharan Africa, are experiencing intensified droughts, food insecurity, and limited access to clean water and reliable energy. At the same time, these regions are striving to develop and improve living standards, which requires balancing environmental, social, and economic priorities under constrained conditions.

Rwanda, a small landlocked country in Sub-Saharan Africa, presents an interesting case. Despite its size and historical challenges, it is pursuing development with ambitious climate goals according to its nationally determined contributions (NDCs). Agriculture remains central to Rwanda's economy, with the majority of the population working in the sector. Consequently, Rwanda stands at the intersection of the water, energy, and food systems. A substantial amount of the world's freshwater use goes to irrigation, and while increased irrigation can enhance agricultural productivity, it also requires energy to operate these systems, as well as careful management of water resources.

This thesis explores how renewable energy systems can support sustainable water management for agriculture. Using a systems perspective, it examines the synergies between water, energy, and food systems in the context of climate change and adaptation for rural development in Sub-Saharan Africa.

1.1 Background

Water, energy and food are fundamental resources for human survival and development. These three systems are deeply interconnected and face similar challenges, particularly in the context of climate change. The United Nations Sustainable Development Goals (SDGs) reflect the goals agreed upon in 2015 in order to address these challenges and achieve sustainability across the globe [1]. Several goals are directly linked to the water-energy-food nexus, specifically SDG 2 ”Zero hunger”, SDG 6 ”Clean water and sanitation”, and SDG 7 ”Affordable and clean energy”. Furthermore, all of these connect to SDG 13 “Climate Action”, which recognises that many Earth systems directly affect food production and access to fresh water. Energy plays a crucial role in the green transition in order to combat climate change. Thus, the SDGs acknowledge that sustainable access to food, water and energy must be prioritised [1].

Water is a prerequisite for life. Even though 70% of Earth’s surface is covered by water, only a portion of it is freshwater and usable for humans [2]. Estimates suggest that only about 2-3% of all water on Earth is freshwater [2]. However, the majority of it is locked away in glaciers, ice caps, and underground aquifers, with only a small fraction available as surface water in lakes, rivers, and wetlands [2]. Water is not only critical for drinking but also for energy generation in hydropower and food production for irrigation. Hydropower does not consume large volumes of freshwater, as the water is returned to the river after passing through the turbines. However, it influences water governance and can lead to political conflicts since dams significantly impact water availability downstream. In addition, electricity can enable water purification technologies for drinking water, such as ultraviolet (UV) disinfection. This method offers decentralized solutions for clean drinking water in remote areas with low energy requirements. At the same time, approximately 70% of all freshwater is used for irrigation in food production [3]. Together, these figures highlight the interconnection between water, energy, and food systems.

Electrification and access to reliable energy are fundamental enablers of development, supporting everything from basic services, such as water purification, to economic productivity and productive uses. Access to electricity has been shown to act as a catalyst for improvements in health, education and economy [4]. In the context of climate change, electricity can be generated from renewable resources such as solar, wind and hydropower, aligning with SDG 13 on combating climate change. By replacing fossil fuel-based energy with renewable sources, electrification using renewable energy sources plays an important role in limiting CO_2 emissions and thereby contributes to achieving this goal. In areas lacking central grid infrastructure, micro-grids offer a possibility with a growing availability and increasingly cost-effective solutions [5]. One study examined the synergies and trade-offs between off-grid solar solutions and the SDGs in Rwanda and identified synergies with 80 out of 196 of the targets and trade-offs with ten [6]. It highlighted that off-grid solar systems support sustainable development but at the same time face challenges such as land competition [6]. Another case study in Tanzania investigated the integration between electric cooking (e-cooking) and solar powered micro-grids [7]. The authors found that the integration of e-cooking in a solar based micro-grid is cost-effective, particularly in a community based setting [7]. Ultimately, electricity access not only supports household needs such as electric cooking, which improves health and food preparation, but also enables agricultural activities that require electricity. One example is the use of electric pumps for irrigation, which can improve food production and resilience to drought in rural areas.

Irrigation is the artificial application of water to support the growth of crops and other cultivated plants. Irrigation can significantly increase crop yields and agricultural productivity [8]. It also enables food production in regions with limited precipitation and can support cultivation in otherwise marginal land, depending on soil conditions and agricultural practices. Irrigation has been a practice since the agricultural revolution thousands of years ago [9]. There are multiple methods for irrigation. Some of them are sprinkler irrigation, surface irrigation and drip irrigation. Sprinkler irrigation uses pressurised systems to distribute water through sprinklers at central emitter points [9]. One assessment of a center-pivot irrigation scheme, a type of sprinkler irrigation system, in Rwanda showed that the water supply was often insufficient, resulting in low system efficiency [8]. However, it also highlighted that effective planning of irrigation water management could improve crop yield, performance of the scheme and the income of the farmers [8]. Surface irrigation is the oldest method of irrigation, which uses drainage canals to deliver water to the crops and typically consumes large amounts of water [9]. Drip irrigation is an emerging irrigation method due to its high efficiency (up to 90%) [9]. Drip irrigation systems can either use pumps to transport water directly from a source to the crops or rely on gravity-fed systems, where water is stored in an elevated reservoir or irrigation dam before being distributed through the drip lines [10]. In this thesis, gravity-fed drip irrigation will be the method considered, where energy is used to pump water to an irrigation dam.

Climate change is already intensifying the pressure on interconnected water, energy, and food systems. Global average surface temperature was reported by the IPCC to be 1.1 °C above pre-industrial values between 2011-2020 [11]. However, more recent measures show that 2024 was the first year with a global average surface temperature above 1.5 °C [12]. Rising temperatures and changing precipitation patterns are expected to increase crop water requirements through higher evapotranspiration and reduced precipitation contributing to the irrigation of crops. Thus, climate change poses another challenge to these interconnected systems.

1.2 Case Study

Rwanda is a small landlocked country in East Africa, surrounded by the Democratic Republic of Congo (DRC) to the west, Uganda to the north, Tanzania to the east, and Burundi to the south. It is characterised by hilly landscapes, green forests, and fertile soils. Rwanda has made significant developments in recent decades, having risen as a nation after the horrific genocide which occurred in 1994. Its electricity grid has significantly expanded over the last couple of years and the installed energy generating capacity has almost doubled since 2017 [13, 14]. The country was one of the first to ban plastic bags in 2008, showcasing strong ambitions regarding sustainability and combating climate change [15]. This is also highlighted in Rwanda's Nationally Determined Contributions (NDCs), which describe the country's efforts to fulfil the Paris Agreement [16]. In its NDCs, Rwanda sets a target to reduce emissions by up to 38% compared to a business-as-usual scenario by 2030, while simultaneously achieving development on a broad scale. This demonstrates the country's ambitious approach to climate action despite significant economic challenges [16].

Rwanda's economy is largely based on the agricultural sector and over a majority of the population works within the sector [17]. The country has traditionally relied on rain-fed agriculture but is now transitioning to technological irrigation solutions and significant benefits are expected to be gained from technological advancements in irrigation systems [18, 19]. This makes Rwanda an interesting case exploring the interconnected water, energy, and food systems.

Therefore, this thesis is based on a case study done in a small village in Rwanda, named Tabagwe. A focus area was chosen for the case study, where the types of crops grown were examined. Engagement with the local population was also conducted to understand the local geography and conditions.

The country is administratively divided into provinces, which are divided into districts, among the districts there are sectors, and within the sectors cells. Tabagwe is the name of a small village as well as a sector in Nyagatare district in the eastern province. It is a village with one secondary school and a health center located in the northeast of Rwanda, close to the border with Uganda [20]. The location of Tabagwe is shown in figure 1.1.

The main road passes through the centre of Tabagwe village, where several small enterprises are located, including a salon, a welding business, a textile shop and, an ICT (Information and Communication Technology) service centre, along with the local market. The national grid follows the main road and consists of a medium-voltage line with some branches extending to the low-voltage grid. Most houses along the main road and in the village centre are connected to the low-voltage grid, but according to local inhabitants, the reliability of the electricity supply is often limited.

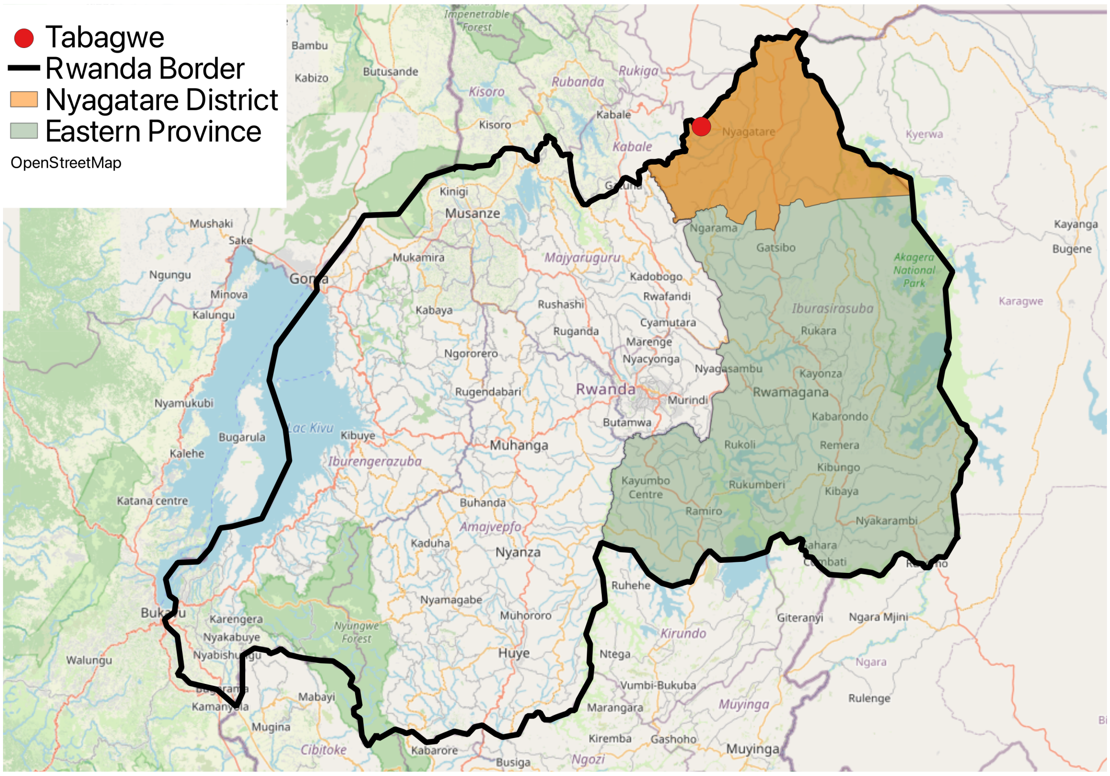


Figure 1.1: Map of Rwanda showing Eastern Province, Nyagatare District, and the location of Tabagwe

1.2.1 The Focus Area

The focus area was chosen near the centre of Tabagwe village where the households are not connected to the grid. It is enclosed by the Kaborogota river and a smaller road along which approximately 150 households are situated. Thus, the potential benefits of electrified irrigation will extend to these households along the road, within the focus area. In Rwanda, and subsequently in Tabagwe, the agricultural year is divided into three seasons, A, B, and C [21]. Season A stretches from September to February, B from March to June, and C from July to September [21]. According to local residents in Tabagwe, season C is only cultivated if modern irrigation methods are implemented, as precipitation during this season is too low to rely on rain-fed agriculture. To identify the three main crops in the focus area, a sample section of the land was mapped to determine which crops were grown and where. The total focus area covers about 95 hectares, with the sample area spanning 50 hectares. This sampling helped establish the predominant crops in the area and served as the basis for calculating irrigation needs. The cultivated area in the focus area is 88 hectares and the rest is made up of roads, grasslands, and houses. The three main crops of the focus area are banana, maize and beans (dry) and the fractional distribution is 51% banana, 30% maize and 19% beans. This is in line with the three main crops of the whole Tabagwe sector, though the distribution differs slightly [22]. Figure 1.2 shows a map of Tabagwe and the focus area.

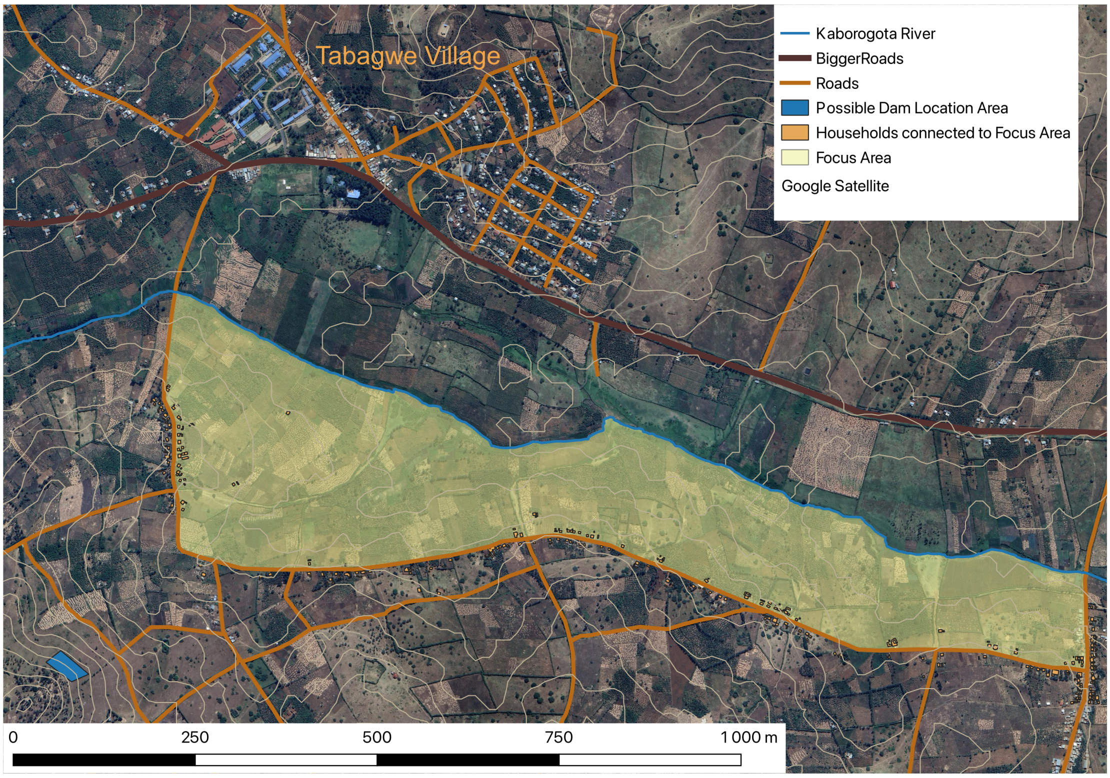


Figure 1.2: Map of the Focus Area, showing the location of the Tabagwe Village centre, smaller roads enclosing the focus area, the Kaborogota River, and the proposed location for a possible irrigation dam. The Focus area, highlighted in yellow, is located outside the village centre and includes approximately 150 households along the smaller road.

1.2.2 Social Circumstances

As Tabagwe is located in a remote area the social circumstances are constrained compared to city life. About 54 000 people live in the sector spread out on 12 600 households, which means an average of 4.3 individuals per household [23]. Since more people often live together in rural settings and to avoid underestimating the number, the average household size in the focus area is assumed to be approximately five. As there are about 150 households in the focus area this results in a population about 750 individuals, which will be used for further calculations in this thesis. Most people in the focus area are involved in agriculture, either producing crops for their own consumption, selling their products, or working for others. If the harvest is sufficient, the surplus is sold at the market as extra income. As the grid is not extended further away from the main road, none of the households in the focus area is connected to the grid. Solar home systems are quite common, consisting of small solar panels around 20-50 W and a small battery. Electricity use commonly includes lighting in the evenings and sometimes at night, as well as charging phones. In the event of more electricity access, many people spoken to wished to develop some sort of small enterprise or business in order to generate an income. This could, for example, be a desire to open a restaurant, owning a maize milling machine or a computer for administrative work. No water utility is connected to the focus area resulting in a walk of around 1 km to the nearest water source located closer to the village centre. This water source is not upgraded nor controlled. Therefore, access to clean drinking water is a high priority of the population.

The case study provided an understanding of the context, culture and daily life in rural Sub-Saharan Africa. It revealed important aspects of local agricultural practices, energy challenges, and community needs, all of which are essential for designing sustainable solutions. The case study significantly influenced the direction of this thesis, and guided the formulation of its aim, research question and objectives.

1.3 Aim

The aim of this thesis is to explore how renewable energy systems can contribute to sustainable development in Sub-Saharan Africa, with a particular focus on agricultural and water systems and their interconnections through integrated solutions in the context of climate change.

1.4 Research Question & Objectives

This aim is addressed through the following primary Research Question:

> *How can renewable energy systems support agricultural water management in rural Sub-Saharan Africa, while addressing trade-offs in the Water-Food-Energy Nexus and building long-term resilience?*

To answer this question, the project is divided into the following objectives:

1. What are the energy demands of electrified irrigation in the focus area in Tabagwe, Rwanda, and how can these findings inform energy-efficient irrigation practices in similar rural settings?
2. How can solar photovoltaics and bio-diesel generators be integrated sustainably and economically to meet the energy demands of electrified irrigation in the focus area of Tabagwe?
3. To what extent can electrified irrigation systems support water purification loads, and what synergies exist between these systems? How can these synergies be optimized to benefit both agricultural and domestic water use?
4. How might climate change impact the energy requirements and costs of electrified irrigation in rural Sub-Saharan areas, such as Tabagwe?
5. How can electrified irrigation and integrated water purification enhance both agricultural productivity and clean water access under climate change projections in rural Sub-Saharan Africa?

1.5 Scope

To explore how renewable energy systems can support water management in rural Sub-Saharan Africa, a systems thinking approach is applied by building knowledge stepwise from a base case to scenario development. The main method is the development, running, and analysis of a linear optimization model representing the needs of the focus area in Tabagwe, Rwanda. The model determines optimal system sizing and operation by minimizing total annual costs.

- The first objective is to quantify the energy demand of an electrified irrigation system serving the three main crops in the focus area. This involves calculating crop water requirements, which scales the energy demand for pumping. Analysing local practices enables identification of opportunities for similar contexts.
- The second objective focuses on sizing the energy system using the model, which includes solar PVs, bio-diesel generators and batteries. Since the model minimizes total annual costs its output reflects cost-effectiveness. Both solar PVs and bio-diesel generators are considered sustainable technologies as they do not emit fossil carbon dioxide. Objectives one and two are addressed through the models base case, Scenario 0.
- The third objective investigates how electrified irrigation systems can support water purification loads by exploring synergies between agricultural and domestic water uses. The scope here is limited to optimizing the connection between these two water management systems and no other water management systems are considered. These interactions are examined through a scenario from the model.
- The fourth objective incorporates climate change impacts on electrified irrigation systems. This is modelled by altering temperature and precipitation patterns, affecting system costs also within a separate scenario.
- Finally, the fifth objective merges previous scenarios to evaluate how system interconnections, performance and costs evolve over time under combined conditions, assessing long-term resilience.

Together, these objectives define the scope of this thesis by focusing on the technical, economic, and environmental aspects of renewable energy systems and their integration with water management, using a specific case study in Tabagwe and drawing broader implications from analysing the results.

1.6 Limitations

Several limitations must be considered in this thesis. The system investigated is geographically limited to the village of Tabagwe in Rwanda, which restricts the generalisability of the findings to other regions with different environmental, social, or infrastructural conditions. In terms of temporal resolution, the model uses data with no more specific intervals than hourly averages, which may limit its ability to capture short-term fluctuations in energy and water demand. The cost specification for energy generation technologies, pumps, motors, and dams does not include detailed or location-specific values for Rwanda. Instead, it is based on general estimates without reference to specific brands or models, potentially affecting the accuracy of the economic analysis.

For irrigation modelling, only the three most common crops grown in the focus area are considered. This selection keeps the analysis feasible and manageable while still representing the dominant agricultural practices in the village, but it may overlook crop-specific water and energy needs beyond those selected. The influence of different fertilizers on water demand is excluded, as the study focuses on the irrigation system and its associated energy demands. However, this exclusion may underestimate water needs if fertilizers affect the water requirements of the crops.

Further, only two water management systems are considered, namely irrigation and water purification. Other systems, such as flood management or drainage, are excluded due to scope limitations, which may lead to an incomplete picture of interactions between water, energy, and food systems in more complex real-world settings. Finally, for the climate change modelling, projections from the IPCC and other scientific sources are used. These are based on global average temperature increases and changes in precipitation patterns specific to East Africa. This method provides a consistent basis for comparing different cases, but it carries uncertainty and may not fully reflect localised climate impacts in Sub-Saharan Africa, potentially affecting the robustness of long-term assessments.

2

Theory

In this chapter, the theoretical background of the agricultural systems necessary for understanding this thesis is presented and explained, followed by descriptions of each technology used in the systems explored in the modelling analysis.

2.1 Irrigation

In agriculture, irrigation can significantly increase agricultural productivity, especially in arid climates. However, the water requirement is substantial and accounts for about 70% of global freshwater use, and is projected to increase in the coming decades [3]. The purpose of irrigation is to restore the water lost through evapotranspiration to ensure that the crops can grow without stress. Evapotranspiration is the combination of water loss from two separate processes, evaporation from the soil in which the plant grows, and transpiration from the plant itself [24]. The FAO method estimates the crop evapotranspiration, ET_c, by calculating the total crop water requirement, which is the multiplication of the reference crop evapotranspiration, ET_0, and the crop coefficient, K_c, and subtracting the effective rainfall, P_e, accordingly

$$ET_c = ET_0 \cdot K_c - P_e \tag{2.1}$$

Evapotranspiration is typically expressed in millimetres, consistent with precipitation measurements.

2.1.1 Reference Evapotranspiration

The FAO Penman-Monteith equation is a method that estimates reference evapotranspiration, and is therefore commonly used to estimate the irrigation water requirement. This equation requires several climate and weather variables, including temperature, relative humidity, solar radiation, and wind speed [24]. The Penman-Monteith equation is expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u_2)} \tag{2.2}$$

Where:

- ET_0 is the Reference evapotranspiration [mm/day]
- Δ is the Slope of the vapour pressure curve [kPa/°C]
- R_n is the Net radiation at the crop surface [MJ/ m^2/day]

- G is the Soil heat flux density [MJ/m^2/day]
- γ is the Psychrometric constant [kPa/°C]
- T is the Mean daily air temperature [°C]
- u_2 is the Wind speed at 2 m height [m/s]
- e_s is the Saturation vapour pressure [kPa]
- e_a is the Actual vapour pressure [kPa].

2.1.2 Effective Rainfall

Not all precipitation is available for crop use. Some water is lost through direct evaporation, surface runoff, or deep percolation beyond the root zone [24]. The portion of rainfall that is actually available for the crop is referred to as effective rainfall [25]. There are multiple methods available for estimating effective rainfall. The USDA method, described in [25], is expressed as

$$\mathrm{P}_{\mathrm{eff}} = \begin{cases} P_{\mathrm{tot}} \cdot \dfrac{125 - 0.2P_{\mathrm{tot}}}{125}, & \text{for } P_{\mathrm{tot}} < 250\,\mathrm{mm} \\ 125 + 0.1 \cdot P_{\mathrm{tot}}, & \text{for } P_{\mathrm{tot}} > 250\,\mathrm{mm} \end{cases} \tag{2.3}$$

where $\mathrm{P}_{\mathrm{eff}}$ is the effective rainfall and $\mathrm{P}_{\mathrm{tot}}$ is the total rainfall, both in millimetres.

2.2 Electricity Generation Technologies & storage

In off-grid irrigation systems, energy generation technologies are needed to supply electricity for the transport of water from the water source to the crops. In this section, the generation technologies and energy storage considered in the systems of this thesis are presented and explained.

2.2.1 Solar Photovoltaic

Whereas solar energy can be harvested in multiple ways, solar photovoltaic is projected to become the largest energy generation technology globally in terms of installed capacity [26]. Solar PVs convert energy from sunlight into electricity by exploiting the band gap of semiconducting materials in the solar cells, typically made from silicon [27]. The cells are assembled into panels, which can be scaled from small solar home systems, small as just a few watts, to large utility-scale solar farms producing several gigawatts. One big advantage of solar PVs is their scalability and modularity, which makes them fit to multiple diverse applications and contexts. A drawback is their dependency on solar radiation, which is intermittent and therefore does not allow electricity production all the time. The tilt angle of the panels should ideally be adjusted to be as close as possible to perpendicular to the incoming solar radiation to maximize electricity generation.

The electricity generation potential of solar PVs depends on the amount of solar irradiance received by the panel surface. This irradiance is affected by the angle of incidence between the sunlight and the panel surface. The irradiance on the plane of array, G_{POA}, can be estimated by adjusting the horizontal irradiance, G_{HI}, according to the cosine of the incident angle as follows

$$G_{\mathrm{POA}} = G_{\mathrm{HI}} \cdot \cos(\theta_i) \tag{2.4}$$

The solar position is typically described using hour angle, solar declination, and solar zenith angle. To estimate the energy output over one hour, the average irradiance (W/m^2) can be converted to energy per installed capacity (kWh/kW). That is done by integrating the irradiance over time and adjusting for panel efficiency and surface area per unit of installed capacity. Then, the conversion is accordingly,

$$E_{\mathrm{kWh/kW}} = \frac{\eta_{\mathrm{solar}} \cdot A_{\mathrm{factor}}}{1000} \int_0^T G_{POA}(t)\, dt \tag{2.5}$$

where:

- η_{solar} is the panel efficiency, [W/m^2],
- A_{factor} is a scaling factor representing the panel area per kW installed [m^2/kW]

The factor 1000 converts watts to kilowatts and the result gives energy in kWh per hour. This allows solar availability to be expressed as energy per unit of installed PV capacity.

2.2.2 Generators running on bio-diesel

Generators are commonly used as backup power sources in the event of grid outages or as a primary power supply in off-grid systems. They generate electricity through electromagnetic induction, where mechanical energy from an internal combustion engine is converted into electrical energy via a synchronous generator. Generators are available in various sizes and configurations and well suited in off-grid settings. The main advantages of using generators in rural areas are their low capital cost, operational flexibility, and controllability. However, they have a high fuel cost. Bio-diesel generators are generally standard diesel generators that either have been adapted or are compatible with bio-diesel fuels [28]. If they are adapted, usually no major modifications are needed [28]. They use the same mature technology as diesel generators but are run on bio-based fuel, which usually affect their performance and have slightly lower efficiency compared to diesel generators [28].

Bio-diesel is an alternative to diesel with approximately the same chemical composition but, unlike normal diesel, it is not made from fossil resources such as crude oil. It can be processed from vegetable oils and biological waste such as manure, animal fats, and waste cooking oil [28].

2.2.3 Batteries

Batteries are a well-known technology for storing energy. Their use is rapidly increasing, driven by the growing need for flexibility in energy systems due to the expansion of intermittent energy sources such as solar and wind power, as well as the rise in electric vehicles [29]. Batteries store electrical energy in the form of chemical potential, enabling both charging and discharging. Among various battery technologies, lithium-ion (Li-ion) batteries are currently the most widely employed [29]. They are rechargeable and characterised by high energy density, long lifetime, and high efficiency [29].

To ensure safe and sustained operation, the rate at which a battery can be charged or discharged is described by the current rate (C-rate). The C-rate indicates the proportion of the battery's capacity that can be charged or discharged within one hour [30]. Lower C-rates are generally preferred, as high C-rates can accelerate battery degradation [30]. Typical C-rates range between 0.2 and 3 [29].

In addition to batteries' technical advantages, batteries involve considerations related to material use and sustainability. The production of batteries requires metals such as lithium, cobalt, and nickel. The extraction and processing of these materials are energy intensive and have environmental impacts [31].

2.3 Pumping Water

Transporting water used for irrigation from the water source to the crops or a storage unit typically requires a pump. In irrigation systems, the most common pumps used are centrifugal pumps [9]. The pump converts mechanical energy, provided by an electric motor, into pressure work to lift the water to a higher elevation. The energy required for pumping is given by

$$E = \frac{m \cdot g \cdot H_{total}}{\eta_{pump}} = \frac{Q \cdot \rho \cdot g \cdot H_{total}}{\eta_{pump}} \tag{2.6}$$

Where,

- E is the energy needed for pumping,
- m is the mass of the water,
- g is the acceleration due to gravity,
- H_{total} is the total head,
- η_{pump} is the efficiency of the pump,
- Q is the water flow,
- ρ is the density of water.

The total head includes both the static head, which is the vertical lift height, and the dynamic head, which accounts for friction losses and velocity head. The dynamic head depends on factors such as pipe diameter, pipe length, flow velocity, and the pipe material. Friction losses increase with higher flow velocity and smaller pipe diameter.

Irrigation pumps can be driven by either alternating current (AC) or direct current (DC) motors. AC motors are more commonly used, particularly in systems connected to the electrical grid or diesel generators [9]. However, DC motors are increasingly used in solar pumping systems, as they can be directly connected to the solar PVs [32]. To allow for flexibility in pump operation under varying demand or energy availability, variable speed drives (VSDs) can be used. These allow the motor to operate at different speeds, adjusting the pumping rate and improving overall system efficiency [33].

2.4 Purifying drinking water with UV light

Clean drinking water is essential for ensuring good health. While most drinking water is sourced from surface freshwater, it often requires treatment before it is safe for human consumption [3]. Among the various purification methods available, ultraviolet (UV) disinfection stands out as a low-energy and chemical-free option, particularly suitable for decentralized and remote settings [34]. UV disinfection works by exposing water to short-wavelength ultraviolet light, which inactivates microorganisms by damaging their DNA or RNA [34]. The effectiveness of UV treatment depends on the UV dose, determined by the light intensity and exposure time. This method is most effective when the water is relatively clear and is therefore often used in combination with filtration, especially for treating turbid surface water [34]. Due to its low energy requirement, UV disinfection can be integrated with solar-powered systems, further enhancing application in rural or off-grid settings. Unlike chlorination, UV disinfection does not produce chemical by-products. However, post purification contamination may appear if not stored safely [35]. In recent years, UV disinfection using LEDs (light emitting diodes) has emerged as a promising option due to its even lower energy requirement and potential for modular, compact system design [36]. Nonetheless, most UV systems currently in use rely on mercury lamps [36]. Although UV disinfection plants are generally low-maintenance, periodic replacement of the lamps is needed to maintain their performance [36].

While other treatment methods, such as reverse osmosis and biofiltration, also use electricity, they differ in application and energy consumption. Reverse osmosis is effective for desalinating seawater but is energy-intensive [37]. Biofiltration uses living microorganisms to purify water and is more energy-efficient compared to reverse osmosis [38].

3

Method

In this Chapter the methodology is explained, starting with an overview of the method and then digging deeper into each of the different Scenarios exploring the objectives of the thesis.

To investigate how renewable energy systems can support the long-term resilience of agricultural water management in rural Sub-Saharan Africa, the main method used was to develop, run, and analyse the results from an energy system model. The model represented an off-grid system designed to meet hourly energy and water needs. It determined both the optimal capacity to install for each technology and how to operate them to fulfil the needs in a cost-effective way. The available technologies were energy generation technologies (including solar PVs and bio-diesel generators), energy storage (battery), a pump and motor, and an irrigation dam. The system generates electricity to run the motor, which pumps water up to the irrigation dam. From there, the water is directed to the farmland when needed and irrigates the crops through a drip irrigation system that relies on gravity-fed distribution due to the dam's height.

The irrigation system in the model covered the focus area and relied on the installed energy technologies to operate the pump, which pumped water from the Kaborogota River, the assumed primary source. The irrigation dam was placed approximately 100 metres higher than the river, resulting in a static head of 100 metres. In addition, 15 metres of dynamic head were assumed to account for friction losses and other resistances in the pipe system, both during pumping to the dam and water release for irrigation. This resulted in a total head of 130 metres being applied in the model.

The model was run for two different system set-ups, the first one included the bio-diesel option referred to as set-up 1, and the second one without that option, thus one fewer technology option, referred to as set-up 2. This was done in order to be able to evaluate the value of the bio-diesel option. The model was formulated as a linear programming problem optimising costs to achieve cost-efficiency and identify the most economical solution. The model was run for a Base Case (Scenario 0) and three additional Scenarios, Scenario 1 (Water Purification), Scenario 2 (Climate Change), and Scenario 3 (Combined: Water Purification & Climate Change), exploring the different objectives presented in the aim.

Several input parameters were required for the model, sourced from different types of data collection. The most important data collection consisted of collecting a comprehensive amount of weather variables over four different years, 2019-2022. The weather variables can be seen in table A.1 in the appendix and were collected from meteorological stations that are part of the TAHMO[1] network in the region close to Tabagwe [39]. The weather variables were collected in hourly time steps and later either used per hour or aggregated into a daily time step. Before being used as input parameters in the model, the two primary parameters were derived through several processing steps from the collected weather data. In addition to the weather data, other technical specifications and cost data were collected generally. The system was modelled on an hourly basis for one year at a time. Since four years of weather data were collected, four separate annual model runs were conducted. Unless stated otherwise, the results presented are average values across these model runs. This averaging was done to capture general trends across the different years, reduce the influence of any single unusually wet or dry year, and to represent what the system would look like to meet the demand a normal year.

3.1 Scenario 0 - Base Case

The base model sized the off-grid energy system and decided its operation to meet the energy demand required for irrigation. The base case was modelled for both system set-ups, corresponding to the two cases S0-1 and S0-2. Although the operation of the pump was decided by the model, the irrigation requirement was preprocessed into the variable Q_t^{in}, which derivation is described in 3.1.1. The second main input parameter was the solar availability, Solar_t, which was a vector describing the solar availability in terms of energy per installed capacity and hour, kWh/kW/hour. This was determined from the solar radiation data and the assumption of a tilt of the panels of 20 degrees as well as an efficiency of 20%.

3.1.1 Water needs

The irrigation requirement was preprocessed into the input parameter containing the irrigation requirement, the Q_t^{in} vector, by first calculating the daily irrigation requirement and then, in order to process the requirements in hourly time steps in the model, an irrigation schedule was established.

The daily irrigation requirement was calculated using the FAO method to calculate the daily evapotranspiration [24]. This method is widely used in agricultural water management to estimate irrigation needs for different crops. For the method, the reference evapotranspiration, the crop coefficients and the effective rainfall were needed according to equation 2.1. In order to determine the reference evapotranspiration, ET_0, the FAO Penman-Monteith equation was used as it is the standard in the FAO method [24]. The crop coefficients as well as the growing times for the three

---

[1] TAHMO stands for Trans-African Hydro-Meteorological Observatory, a network of automated weather stations providing real-time local climate data.

main crops considered were sourced from the Food & Agriculture Organisation [40]. Only the highest crop coefficients were considered for the whole cultivation period. This decision was taken to not restrict the farmer and to demonstrate a worst case approach in order to make sure the requirement is rather too high than too low. This was done for every day in the aggregated daily data collected. When data was missing the value was set to the mean value of the dataset. The evapotranspiration was calculated by multiplying the reference evapotranspiration with the crop coefficient. This was then scaled to the focus area. To calculate the effective rainfall the USDA method was used as recommended for areas with water shortage [41].

After the daily irrigation requirement was calculated, the vector was transformed from a daily time step to an hourly time step in order to finalise the input parameter Q_t^{out}. To process the irrigation requirement, an irrigation schedule was constructed where the daily irrigation requirement was distributed across the hours for irrigation. The most suitable hours for irrigation are early in the morning and late afternoon in order to have a minimal impact from a higher evaporation during the day [42]. Therefore, the irrigation schedule allocated the daily irrigation requirement and spread out between 6-10am and 8-10pm, if the flow became too high the irrigation hours were extended to a maximum of 10 hours a day to avoid exceeding the physically possible irrigation flow. The maximum flow used was 700 m^3/h. When the hourly irrigation schedule was finalised, the input parameter of the irrigation requirement was ready to be used in the model as the hourly vector Q_t^{out}, further explained in section 3.1.2.

3.1.2 Linear Optimization & Energy system modelling

The linear optimisation model was developed from the system components, several input parameters, physical and modelling constraints as well as the objective function, minimizing the total annual cost. Apart from the two primary inputs, the irrigation requirement, Q_t^{out}, and solar availability, Solar_t, parameters such as cost data and efficiency values, are provided in the appendix A.2. In this section, the different constraints governing the model are presented as well as the objective function.

Model Constraints

The dam level constraint kept track of the pumped water flowing into the dam and the outflow given by the irrigation requirement input. It connected the requirements for irrigation to the energy needed to run the pump. The initial dam level was set to 2000 m^3, representing the minimum allowable volume in the dam, which is 10% of the dam's total capacity. As a consequence, the dam's maximum capacity cannot exceed 20 000 m^3, a limit based on the available land area for the irrigation dam. However, the capacity of the dam can be smaller, in which case the starting volume is above the minimum allowed level. The last hour of the year required the dam to hold at least the same amount of water as it began with. The constraint was defined as

$$V_t = V_{t-1} + Q_t^{\text{in}} - Q_t^{\text{out}}, \quad \forall\ t \in T \tag{3.1}$$

where:

- V_t is the volume of water in the dam at time t $[\text{m}^3]$,
- Q_t^{in} is the pumped inflow to the dam at time t $[\text{m}^3/\text{h}]$,
- Q_t^{out} is the irrigation demand (i.e., outflow from the dam) at time t $[\text{m}^3/\text{h}]$.

The dam was also governed by a capacity constraint, so that the level of the dam cannot exceed its capacity. Additionally, a minimum of the dam level of 10% of its capacity was set so that the dam is not completely emptied which also ensured sustainability of the dam operation. The constraints were defined as

$$V_{max} \geq V_t, \quad \forall\ t \in T \tag{3.2}$$

$$V_t \geq V_{max} \cdot 0.1, \quad \forall\ t \in T \tag{3.3}$$

where V_{max} is the maximum volume of water in m^3 the dam can hold.

The energy required for the pump to lift water from the river to the irrigation dam was, according to the energy equation,

$$E_t^{\text{pump}} = \frac{Q_t^{\text{in}} \cdot \rho \cdot g \cdot H_{tot}}{\eta_{pump} \cdot 3.6 \cdot 10^6} \quad \forall\ t \in T \tag{3.4}$$

where:

- E_t^{pump} is the energy required to pump water at time t [kWh],
- ρ is the density of water, equal to 1000 $[\text{kg}/\text{m}^3]$,
- g is gravitational acceleration, 9.81 $[\text{m}/\text{s}^2]$,
- H_{tot} is the total dynamic head [m],
- Q_t^{in} is the volume of water pumped at time t $[\text{m}^3/\text{h}]$,
- η_{pump} is the efficiency of the pump, assumed to be 0.7.

The water flow that was pumped was constrained by the capacity of the pump according to

$$P_{pump} \geq E_t^{\text{pump}}, \quad \forall\ t \in T \tag{3.5}$$

Here, P_{pump} is the rated power of the pump in kW, which is dimensionally equivalent to kWh/h which are the units of E_t^{pump} when integrated over time. Thus, a simplification was made since this is not the instantaneous power of the pump, but it reflects the average energy consumed per hour.

Next, the Demand-Supply constraint connects the energy consumed and the energy generated in the system. The total energy consumed at each time step must be met by the combination of electricity produced by the solar PVs and the bio-diesel generator, and from battery discharging, as well as the electricity used for charging the battery. This was represented by the following constraint:

$$E_t^{\text{pump}} + bat_t^{\text{charge}} \leq E_t^{\text{solar}} + E_t^{\text{bio}} + bat_t^{\text{discharge}}, \quad \forall\ t \in T \tag{3.6}$$

where:

- E_t^{pump} is the energy consumed by the pump at time t [kWh],
- bat_t^{charge} is the energy used for charging the battery at time t [kWh],
- E_t^{solar} is the energy generated by solar power at time t [kWh],
- E_t^{bio} is the energy generated by biomass at time t [kWh],
- $bat_t^{\text{discharge}}$ is the energy discharged from the battery at time t [kWh].

The electricity produced from solar was determined by the input vector Solar_t and the decision variable C^{solar}. The input vector Solar_t describes the potential electricity production per unit of installed capacity, given in kWh/kW, which was further described in Section 3.1. The decision variable C^{solar} represents the installed solar capacity in kW. The energy generation from solar at each time step was then defined as

$$E_t^{\text{solar}} = \text{Solar}_t \cdot C^{\text{solar}}, \quad \forall\, t \in T. \tag{3.7}$$

The electricity produced by the bio-diesel generator was, unlike solar, not dependent on weather conditions and can be operated as needed. Therefore, E_t^{bio} was modelled as a decision variable. However, it could not exceed the generator's installed capacity, which was also a decision variable. The relationship between the two was defined as

$$E_t^{\text{bio}} \leq C^{\text{bio}} \cdot \eta_{bio}, \quad \forall\, t \in T \tag{3.8}$$

Here, C^{bio} denotes the installed capacity of the bio-diesel generator in kW, and η_{bio} is its efficiency. The efficiency term was not part of the solar equation was because it was included in how the vector Solar_t was calculated.

The battery was constrained by both its energy storage capacity and its charge and discharge C-rates. The charge rate was set to 0.2 C, meaning the battery could be fully charged in 5 hours, and the discharge rate was set to 0.5 C, allowing full discharge in 2 hours. The lower charge rate was set to protect battery health, while the higher discharge rate allows the battery to meet demand peaks when needed. These values are also within the typical range for C-rates for batteries used in off-grid systems. These constraints are captured by the following three equations

$$SOC_t \leq C^{\text{battery}} \tag{3.9}$$

$$bat_t^{\text{charge}} \leq C^{\text{battery}} \cdot \text{ChargeRate}, \quad \forall\, t \in T \tag{3.10}$$

$$bat_t^{\text{discharge}} \leq C^{\text{battery}} \cdot \text{DischargeRate}, \quad \forall\, t \in T \tag{3.11}$$

Where:

- SOC_t is the state of charge of the battery [kWh],
- ChargeRate is the maximum power rate of which the battery can charge, set to 20% of the battery's capacity,
- DischargeRate is the maximum power rate of which the battery can discharge, set to 50% of the battery's capacity.

Lastly, the model is directed by the costs of each technology, both capital expenditures and operational, variable and maintenance costs. The equation for the total annual CAPEX is

$$\text{CAPEX}_{tot} = \sum_{g \in G} C_g \cdot \text{CAPEX}_g \cdot \text{CRF}_g \tag{3.12}$$

where:

- C_g represents the decision variable for the installed capacity or size of each component (solar, bio-diesel, battery, pump and dam size),
- CAPEX_g is the capital expenditure in \$ per unit for each technology,
- CRF_g is the capital recovery factor for each component[2].

The rest of the annual cost, the operational, maintenance and variable cost is calculated as one and is governed by

$$\text{OPEX}_{tot} = \sum_{g \in G} C_g \cdot \text{CAPEX}_g \cdot \text{OPEX}_g + \sum_{t \in T} E_t^{bio} \cdot \text{FuelCost} \tag{3.13}$$

and here, OPEX_g is a percentage which is the assumed operational and maintenance costs for all components, set to 5%. The cost for bio-diesel fuel, FuelCost in equation 3.13, was calculated in \$/kWh energy generated.

Objective Function

The objective function was to minimize the total annual cost, with the aim of sizing a cost-effective system, given by

$$\min \text{CAPEX}_{tot} + \text{OPEX}_{tot}. \tag{3.14}$$

Additional model set-up is found in the appendix. The base case for the model was run for the two model set-ups; set-up 1 including the bio-diesel generator and set-up 2 without. For set-up 2 the cost for bio-diesel was set very high so that the model did not choose that option, otherwise the model construction looked the same.

---

[2] The CRF is more explained in Appendix, see section A.2

3.2 Scenario 1 - Water Purification

To investigate the extent to which electrified irrigation systems can support water purification loads, Scenario 1 modelled the system covering both irrigation and water purification. By doing so, the synergies between electrified irrigation powered by renewable energy and other loads were also investigated.

The choice of method for purifying water was ultraviolet (UV) disinfection due to its low energy demand and low cost [34]. The Scenario was modelled for 750 people who were assumed to live in the proximity of the focus area. The Scenario was modelled for both set-ups of the system across several cases. The cases involved fixed water purification schedules, where the system had to meet a fixed demand, and opportunistic cases, where the purification was only done with surplus energy and no extra investment was done.

The cases with fixed water purification used the same model layout as the Base Case (Scenario 0) but with a change in the Supply-Demand constraint as well as a new constraint limiting the bio-diesel generator so that it was not available to be used for the water purification. That limitation was set to prioritise bio-diesel use for peak irrigation demand only, as the aim was to assess how the irrigation system can support the added water purification load.

The different water purification schedules was implemented as a load in the energy system model, corresponding to E_t^{Purif}, and is added in the Demand-Supply constraint as

$$E_t^{\text{pump}} + bat_t^{\text{charge}} \leq E_t^{\text{solar}} + E_t^{\text{bio}} + bat_t^{\text{discharge}} + E_t^{Purif}, \quad \forall\, t \in T \tag{3.15}$$

As the UV disinfection was not allowed to run on bio-diesel, one new constraint was needed which was

$$E_t^{Purif} \leq \text{Solar}_t \cdot C^{solar} + bat_t^{discharge}, \quad \forall\, t \in T \tag{3.16}$$

which assured that the purification load was met either by solar directly or by stored energy from the battery.

The cases with fixed water purification included two different volumes per person and day, 20 litres and 50 litres, and two different operational approaches, constant water flow and only daily water flow (between 06:00 am-06:00 pm). These levels were chosen according to the World Health Organization's (WHO) recommendation of basic access (20 litres per day) and intermediate access (50 litres per day) [43]. Cases with a fixed purification schedule but with no irrigation were also investigated, limited to set-up 2, as bio-diesel was not used for water purification. Furthermore, a comparative case with grid supplied water purification was also calculated.

The cases with fixed water purification schedules accounted for twelve different cases, each with a unique case ID. For example, the case ID S1-W20c-1 denotes that it belongs to Scenario 1, purifies 20 litres of water per person a day at a constant water flow, and uses system set-up 1. On the other hand, the case ID S1-W50d-ni-2 denotes that it belongs to Scenario 1, purifying 50 litres per person a day at a daily flow, has no irrigation demand, and uses system set-up 2. The grid supplied case has the case ID S1-W-G. All the cases and their descriptions can be seen in the appendix A.5.

The opportunistic cases used the model layout as the Base Case (Scenario 0) and then explored what opportunities there were in the surplus energy generated throughout the year. These cases are referred to as S1-WO-1 and S1-WO-2, as in Scenario 1, water purification opportunistic for either set-up 1 or 2.

The cost of the UV disinfection system was added each year on the total annual cost, so there was no need for accounting for the capital recovery factor. This is due to the operational lifetime of the UV lamps, consisting of the majority of the cost, being around 9000 hours [36]. Therefore, the UV disinfection system was assumed to need replacement every year for the constant cases and every second year for the daily cases. This results in the same annual cost for the constant and the daily systems providing the same volume of water per day. The cost is assumed to be linear and is based on a system costing 13.71 thousand dollars, with a capacity of 100 m^3/day [44]. This system uses UV disinfection for ”non-potable water” and to account for additional purification required to make the water potable, the cost was doubled. The costs for the different systems used can be seen in table A.4 in appendix. For the opportunistic cases, the cost was calculated using the same approach, based on the maximum hourly capacity of purified water and the number of operational hours. Here 4000 hours per year were used, reflecting the average number of hours with available surplus energy. The energy requirement for the process in the model is set to 0.023 kWh/m^3, in accordance with [34], when purifying turbid water.

3.3 Scenario 2 - Climate Change

To see how climate change might impact the energy demand and costs of electrified irrigation, the model was run under a climate change Scenario. This Scenario explored three different climate projections for both set-ups, resulting in six different cases. The cases were based on the temperature and precipitation projections presented in the IPCC Sixth Assessment Report (AR6), derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The Scenarios reflect three different Shared Socioeconomic Pathways (SSPs): SSP1-1.9, SSP3-4.5, and SSP5-8.5, representing low, intermediate, and high emission futures, respectively. However, these are referred to in terms of their associated global temperature increases: 1.6°C, 2.0°C, and 2.4°C. Projected changes in both temperature and precipitation were incorporated according to the global averages reported in AR6 and supplemented by additional precipitation change data from [45]. The cases and how they were modelled are presented in table 3.1.

Table 3.1: Table showing modelled climate change projections for global average temperature increase and precipitation changes in Eastern Rwanda across different IPCC Scenarios. The table includes the six different climate change cases modelled with their corresponding case IDs, connecting SSP Scenarios, modelled temperature increase in °C, precipitation projections and the modelled precipitation changes, as well as the sources of the data.

Case ID	Set-up	IPCC Connecting Scenario	Modelled Temperature Change [°C]	Precipitation Change Eastern Rwanda	Modelled Precipitation Change	Source
S2-C1.6-1	1	SSP1-1.9	+1.6	-	+1%	[11] [45]
S2-C1.6-2	2	SSP1-1.9	+1.6	-	+1%	[11] [45]
S2-C2.0-1	1	SSP2-4.5	+2.0	MAM +0 - 5% Dry season -0-5%	MAM +5% Dry season -5%	[11] [45]
S2-C2.0-2	2	SSP2-2.5	+2.0	MAM +0-5% Dry season -0-5%	MAM +5% Dry season -5%	[11] [45]
S2-C2.4-1	1	SSP5-8.5	+2.4	MAM +5-10% Dry season -5-10%	MAM +10% Dry season -10%	[11] [45]
S2-C2.4-2	2	SSP5-8.5	+2.4	MAM +5-10% Dry season -5-10%	MAM +10% Dry season -10%	[11] [45]

As the climate change cases only alter the input parameters Solar_t and Q_t^{out}, the model stays the same as in the Base Case (Scenario 0), with only the input parameters altered.

3.4 Scenario 3 - Combined: Water Purification & Climate Change

The last Scenario investigated how electrified irrigation and integrated water purification could enhance agricultural productivity and clean water access under the different climate change projections. Accordingly, Scenario 3 examined a combination of the previous Scenarios. This Scenario did not combine all cases possible, as this would involve an unmanageable number of cases, but instead focused on the most relevant ones. It explored the last objective from two different angles, first from capturing the cost of adaptation, and secondly the impacts on the performance without any adaptation.

The first angle, exploring the cost of adaptation, combined the fixed water purification schedule cases with daily flow for both volumes and the climate projections. The combinations were applied for both system set-up 1 and system set-up 2. The cases were run in the model covering both the water purification load and the altered input parameters due to climate change.

The second angle focused on investigating the system's performance if it were not adapted to withstand climate change under the different climate change projections. Figures showing the extent to which the system could still meet the demand, expressed as a percentage, were calculated. This was done under two different approaches. In the first approach, irrigation was prioritised to fill its demand as much as possible before giving the remaining available power to the water purification system. In the second, the water purification system was prioritised over the irrigation load. This was done to examine how conflicting interests might evolve and what outcome this might lead to. This angle included both daily and constant water purification flows but considered only system set-up 1.

In total, 14 cases were examined for this Scenario, as shown in table A.5. For example, the case with the ID S3-W50d-C2.4-1 represents the combined case for Scenario 3, purifying 50 litres of water per person per day under the climate change projection corresponding to an increase of 2.4°C in temperature and uses system set-up 1.

4

Results

The results chapter follows the same structure as the Method. It presents the Scenarios in the order they were introduced. It begins with Scenario 0, the Base Case, which focuses on the water and energy needs of electrified irrigation and how solar photovoltaics and bio-diesel generators can be combined to meet these needs in a sustainable and cost-effective manner. Scenario 1 presents the water purification results and examines how electrified irrigation systems can support this additional load and how the two services interact. Scenario 2 presents the effect of climate change, highlighting its influence on energy demands and system costs. Lastly, Scenario 3 brings these two dimensions together. It analyses how the integrated system can support both agricultural productivity and clean water access under the impacts of climate change.

4.1 Scenario 0 - Base case

In this section, the results for the Base Case are presented, starting with the irrigation requirements and energy demands. These results are followed by an overview of the energy system layouts, generation, and operation for both system set-up 1 and 2. The section then presents the system costs, followed by an analysis of the system efficiencies.

4.1.1 Water & Energy Needs

The demand for energy in irrigation comes from the pumping of water. The amount of water needed depends on the crops being grown. For the three main crops grown in the focus area, banana, maize and beans, the maximum crop coefficient K_c values are shown in Table 4.1. The cultivation dates used for each crop are also given, based on current agricultural practises. Bananas are cultivated all year round, while Maize are cultivated in season A, from September to the end of February, and beans have a slightly shorter growing cycle, from beginning of March to mid-June.

Table 4.1: Table of crop coefficients (maximum K_C values) and cultivation periods for bananas, maize and beans, showing the lenght of the growing season in days and the start and end dates of cultivation.

Crop	**Kc max**	**Cultivation time [days]**	**Cultivation Start [date]**	**Cultivation End [date]**
Banana	1.2	365	Jan 1st	Dec 31st
Maize	1.2	110	Sep 1st	Feb 27th
Beans	1.15	180	Mar 1st	Jun 18th

The evapotranspiration throughout the year is directly proportional to the crop coefficient and the cultivation schedule. The irrigation requirement for one hectare of the focus area is shown in figure 4.1. The figure shows both the total monthly water requirement for the crops, and the contribution from effective rain as well as the net water requirement which needs to be met through additional irrigation. It can be observed that banana cultivation has the highest water requirement. This is due both to bananas being grown all year round and to the area distribution between the three crops presented in section 1.2.1. Maize requires slightly more water than beans, which is caused by the area distribution and the smaller crop coefficient for beans. The focus area benefits most from effective rainfall in December, but there is a lack of rain during July. The highest net water requirement, i.e., the irrigation requirement, occurs in January.

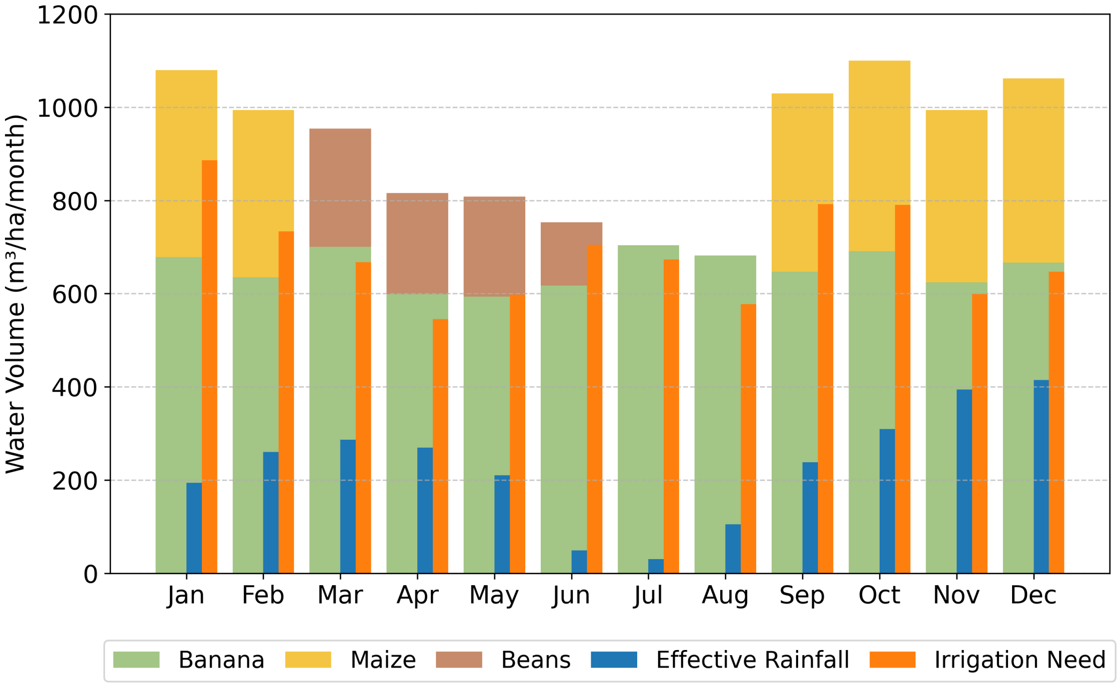


Figure 4.1: Monthly irrigation requirement per hectare for the focus area, averaged over four years of data. The stacked bars show total crop water requirement (banana in green, maize in yellow and beans in brown). Smaller bars show effective rainfall (blue) and net irrigation requirement (orange).

As the crop coefficient and the cultivation schedule scale the irrigation requirement, the irrigation requirement, in turn, scales the energy demand for irrigation. The monthly energy demand per hectare is presented in figure 4.2. Since both set-up 1 and set-up 2 have the same irrigation requirement, though with a different pumping pattern, the energy demand is the same when summed over time, with only minor variations at shorter time intervals. Therefore, the monthly energy demand is shown only for set-up 1, as the difference is negligible. It can be seen that, similar to the irrigation requirement in figure 4.1, the energy demand peaks in January, with an energy demand of approximately 450 kWh/ha/month. The average monthly energy demand is about 340 kWh/ha which is equivalent to an average daily energy demand of approximately 11 kWh/ha/day.

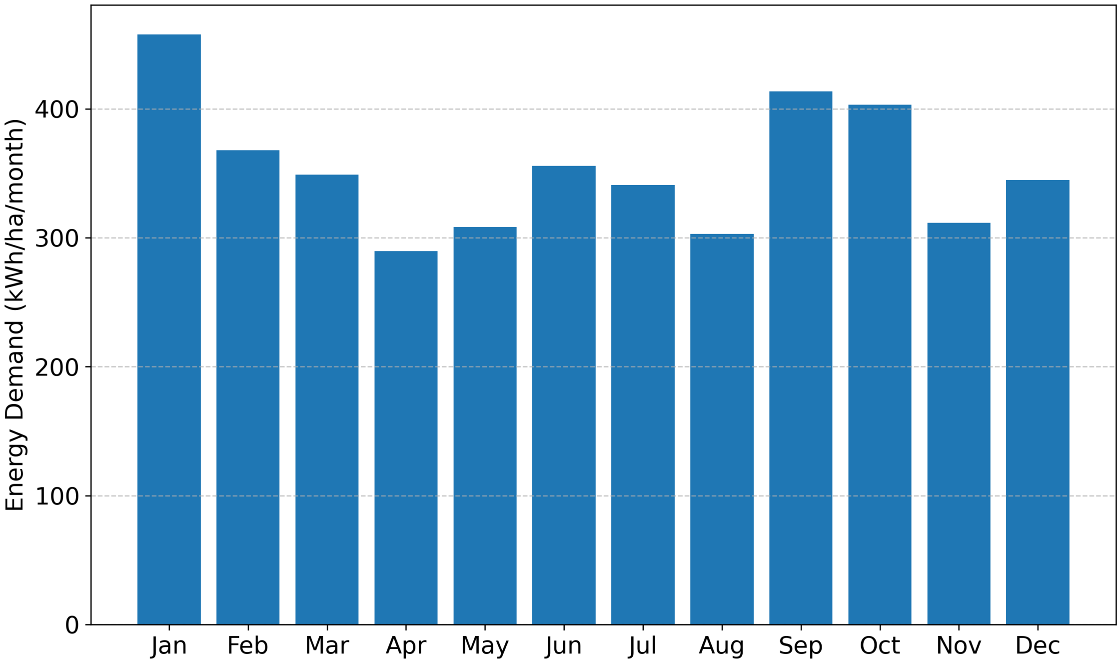


Figure 4.2: Monthly energy demand per hectare for irrigation in system set-up 1, averaged over four years. The same energy demand was observed for system set-up 2.

4.1.2 System Design & Operataion

To meet the demand, the energy system model finds an optimal solution for doing so in a cost-effective way. The optimal system layouts to meet the demand in the Base Case, with the two different model set-ups, are presented in Table 4.2. The layout is given for the entire system, which covers electrified irrigation for the full focus area of 88 hectares. It reveals that 90 kW less solar capacity is needed in set-up 1, where instead 40 kW bio-diesel capacity is installed. The pump capacity is also larger in the results from model set-up 2 compared to set-up 1. The dam is larger for system set-up 1 compared to system set-up 2. Neither system includes investment in battery storage in the Base Case solution.

Table 4.2: Optimal system layout for Scenario 0 (the Base Case) for set-up 1 (case S0-1) and set-up 2 (case S0-2), showing the optimal installed capacity required to cost-effectively meet the demand for each system component. Cost data used in the model for each technology is provided in Appendix A.2 and A.3.

System Component	**set-up 1**	**set-up 2**	**Unit**
Solar Capacity	400	490	kW
Bio-Diesel Capacity	42	-	kW
Battery Capacity	0	0	kWh
Pump Capacity	250	308	kW
Dam Capacity:	10510	7850	m3

The systems' operational patterns differ between system set-up 1 and system set-up 2. Figures 4.3 and 4.4 show the daily energy generation for system set-up 1 and system set-up 2, respectively, in the Base Case Scenario. As system set-up 2 installs about 90 kW more solar PVs it also produces more electricity overall. In figure 4.3 the operation of the bio-diesel generator in system set-up 1 can be seen, covering the highest peaks of demand. The highest daily energy generation is about 1770 kWh for set-up 1 and 2160 kWh for set-up 2.

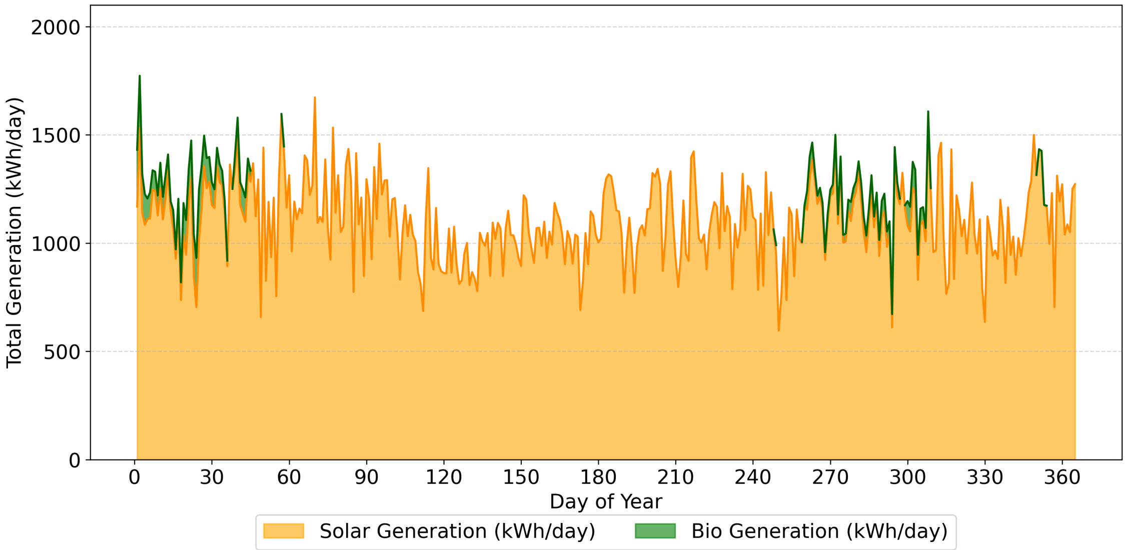


Figure 4.3: Daily energy generation in the Base Case for system set-up 1 (case S0-1), showing contributions from solar and bio-diesel generator over the modelled period.

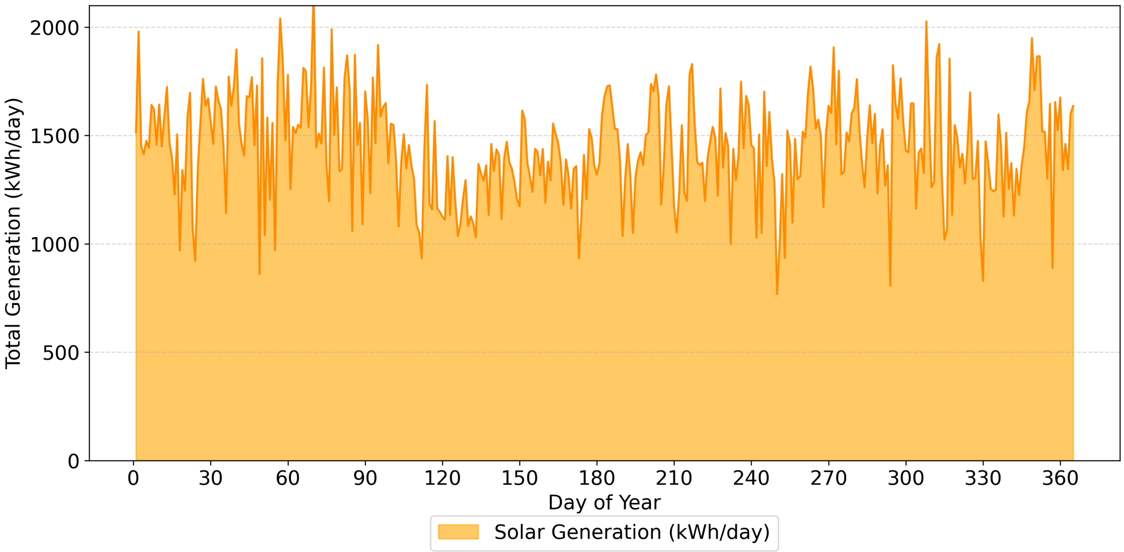


Figure 4.4: Daily energy generation in the Base Case for system set-up 2 (case S0-2), showing solar generation over the modelled period.

Figure 4.5 presents the dam levels per day for both set-up 1 and set-up 2 in the Base Case Scenario. The dam level behaviour follows a similar pattern for both systems. However, due to the larger dam size in set-up 1, the dam level is generally higher. This difference is likely because set-up 2 has a larger pump capacity, allowing it to store water more efficiently, while set-up 1 needs a larger dam to cover higher peaks in irrigation demand during periods of lower solar generation.

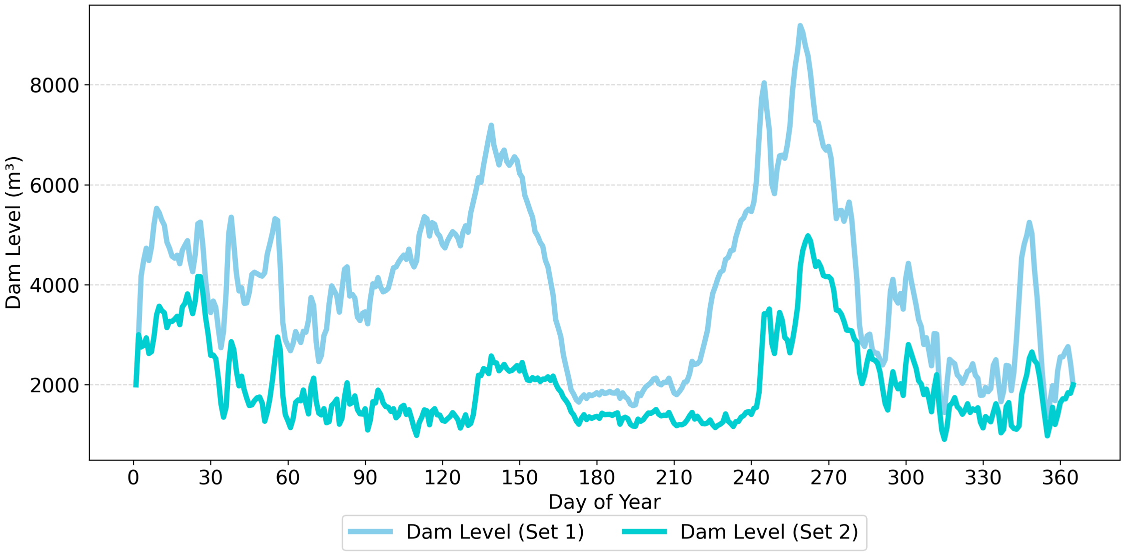


Figure 4.5: Daily dam levels over time in the Base Case for system set-up 1 (case S0-1) and system set-up 2 (case S0-2)

4.1.3 System Cost

In figure 4.16 the annual costs for the Base Case for the two different system set-ups are shown in two pie charts to illustrate the cost distribution between the different components of the systems. The figure shows that the cost for system set-up 1, including bio-diesel, is cheaper while system set-up 2, with only solar, is almost 7% more expensive. System set-up 1 costs about 58 thousand dollars per year, and system set-up 2 costs about 63 thousand per year. The solar panels are the highest cost for both system set-ups and the cost for the dam is the smallest. The second most expensive component for both set-ups is the pump. For system set-up 1, the third highest cost is the generator and the bio-diesel fuel, each corresponding to approximately the same percentage of the total annual cost.

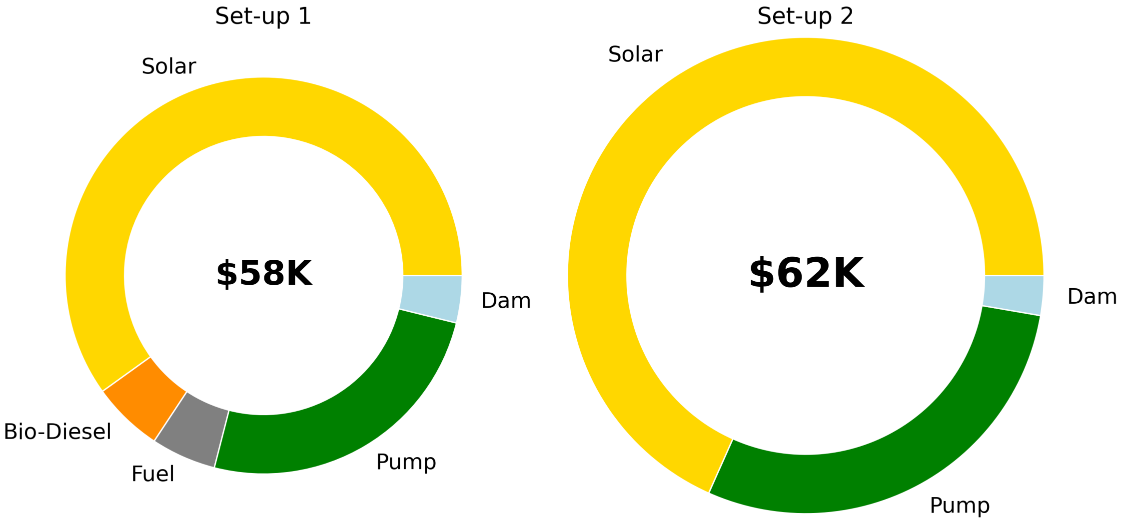
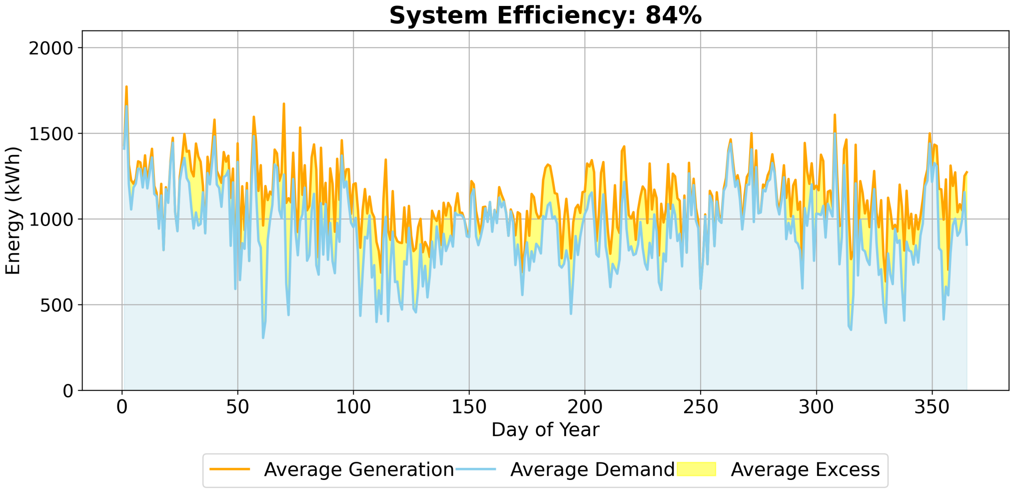


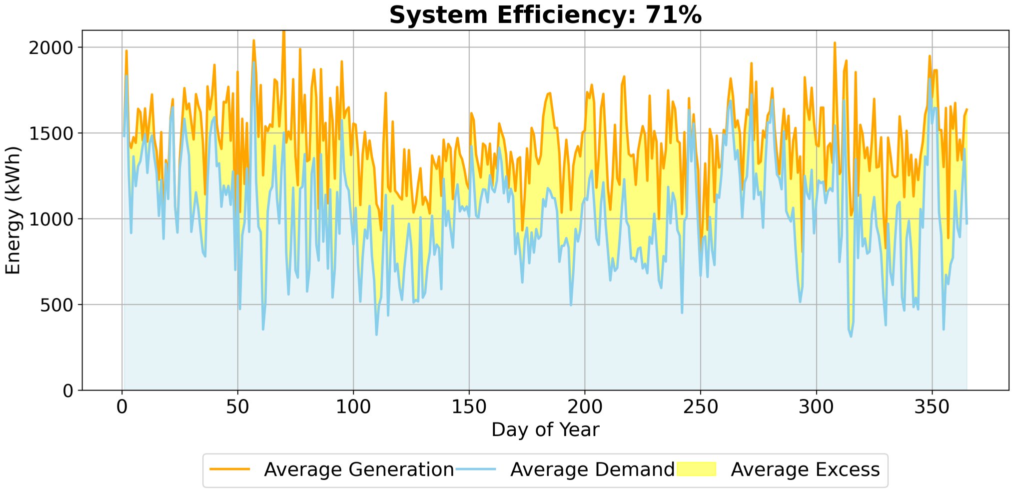
Figure 4.6: Total annual cost and cost distribution for the Base Case, shown as pie charts for system set-up 1 (case S0-1) and system set-up 2 (case S0-2). The figure compares the cost breakdown across system components.

4.1.4 System Efficiency

The final figures presenting the base case results show the overall efficiency of each system and the surplus energy over the year. These are shown in figure 4.7. It reveals that the overall system efficiency of system set-up 1 and system set-up 2 are 84% and 71% respectively. This suggests that system set-up 1 has less potential to be used for other purposes but is, as previously demonstrated, more efficient and more cost-efficient.



(a) System efficiency and surplus energy for set-up 1 in the Base Case (case S0-1), showing the share of demand relative to total generation and the amount of excess energy over the year.



(b) System efficiency and surplus energy for set-up 2 in the Base Case (case S0-2), showing the share of demand relative to total generation and the amount of excess energy over the year.

Figure 4.7: Comparison of system efficiency and annual surplus energy between set-up 1 and set-up 2 in the Base Case.

4.2 Scenario 1 - Water Purification

This section presents the findings of the water purification Scenario, showing the extent to which electrified irrigation can support this extra load and at what cost. First, the cases with fixed schedules are presented together with a comparison of the grid-supplied case. Then, the opportunistic cases are presented.

4.2.1 Fixed purification Schedule

In the cases investigating a fixed schedule for water purification, both system set-ups start to invest in battery capacity. This is as expected since the Supply-Demand constraint now consists of a fixed load during fixed hours under times with no available solar. Even in the daily cases, this outcome is expected, since the water purification load starts 6:00 am and ends at 6:00 pm, covering hours when, on some days, no solar energy is available. The investments in battery storage are shown in Table 4.3. Both set-up 1 and 2 have an insignificant change of investment for the other technologies except the battery. Comparing the constant and daily flow schedules, slightly more battery investment is required for the daily flow schedules. However, no significant difference was observed between the two set-ups.

Table 4.3: Optimal battery storage capacity investment under the fixed schedules for water purification, presented for Scenario IDs S1-WXXc-X and S1-WXXd-X. The Table shows the optimal battery capacity in kWh required for both set-up 1 and set-up 2 across the different fixed schedules for water purification.

Set-up 1 - Case-ID	**W20c-1**	**W20d-1**	**W50c-1**	**W50d-1**	**Unit**
Optimal Battery Capacity:	0,2	0,1	0,4	0,2	kWh
Set-up 2 - Case-ID	**W20c-2**	**W20d-2**	**W50c-2**	**W50d-2**	**Unit**
Optimal Battery Capacity:	0,2	0,1	0,5	0,2	kWh

In Table 4.4, the cost development for the different fixed cases and for both set-ups is shown. It also states the extra annual cost compared to the Base Case. The cost increases more for system set-up 1 in the 20-litre cases compared to system set-up 2, but in the end the cost increase is about the same for the 50-litre cases, leading to system set-up 1 remaining the cheaper set-up. This is the case, even though bio-diesel is not allowed to be used for purifying water. The highest cost increase can be seen for the cases purifying 50 litres per person per day with system set-up 1, with no indicative difference between the constant and the daily flow cases (cases S1-50c-1 and S1-50d-1). For these cases, the cost increases by about 19% compared to the Base Case (S0-1). However, the same figure for system set-up 2 is a cost increase of about 18%, which indicates that the cost increase is almost the same for the different set-ups.

Table 4.4: Total annual cost and percentage increase in cost compared to the Base Case for water purification cases with fixed schedules, identified by the case IDs S1-XXc-X and S1-XXd-X. Cost values are presented in thousand dollars per year for both system set-up 1 and system set-up 2.

Set-up 1 - Case-ID	**S0-1**	**S1-W20c-1**	**S1-W20d-1**	**S1-50c-1**	**S1-50d-1**
Total Annual Cost [k$/year]	58	63	63	69	69
Percentage Cost Increase [%]	-	9	9	19	19
Set-up 2 - Case-ID	**S0-2**	**S1-W20c-2**	**S1-W20d-2**	**S1-50c-2**	**S1-50d-2**
Total Annual Cost [k$/year]	62	66	66	73	73
Percentage Cost Increase [%]	-	6	6	18	18

The marginal cost per litre of purified water is shown in Figure 4.8. Light blue and turquoise bars represent the cases with a fixed purification schedule for system set-up 1 and system set-up 2, respectively. Gray bars indicate cases without irrigation demand (S1-W20c-ni-2, S1-W20d-ni-2, S1-W50c-ni-2, and S1-W50d-ni-2), while the yellow bar shows the marginal cost of grid-supplied purification for comparison (i.e., the S1-W-G case).

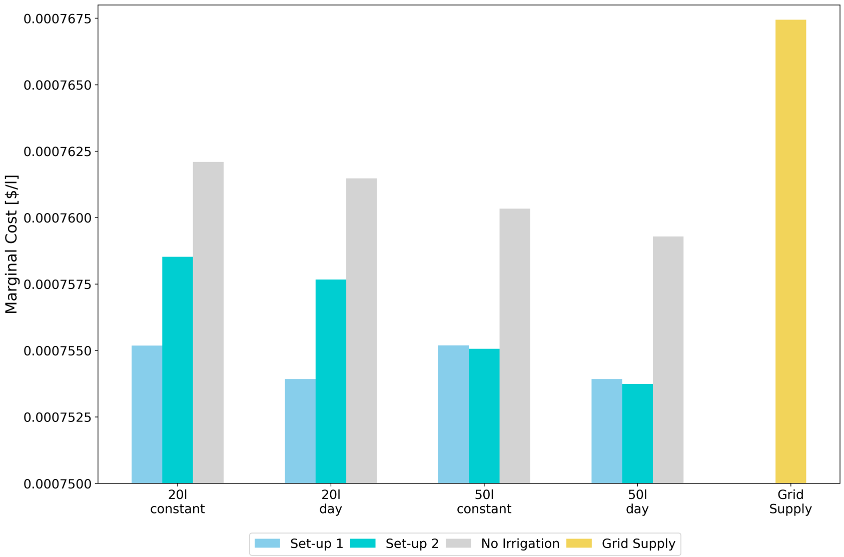


Figure 4.8: Marginal cost per litre of purified water for all fixed water purification Scenarios. Results are shown for both system set-up 1 and system set-up 2, including cases without irrigation demand and the case with grid-supplied water purification. Note that the vertical axis does not start at zero to highlight differences and patterns.

Note that the vertical axis of the plot does not start at zero. This enables clearer comparison of patterns among the cases. For system set-up 1, the marginal cost of purified water is higher for the constant fixed schedule. This is due to a larger investment in battery storage for the constant cases. In contrast, for set-up 2, the marginal cost becomes smaller the more water is purified, at least when comparing the 20-litre and 50-litre cases. However, the daily cases also have lower marginal costs than the constant schedule. That the cases purifying larger volumes of water have a smaller marginal cost for set-up 2 is likely because the system efficiency becomes higher when more energy can be used for another load, showcasing a synergy between system set-up 2 and the electrified irrigation system. The case with no irrigation demand is more expensive per litre of purified water, and follows the same pattern as system set-up 2. All cases show a smaller marginal cost when compared with the grid-supplied case. However, the difference between the cheapest and most expensive cases supplied by the irrigation system is less than 0.01 cent per litre, or a percentage difference of 1.07%. The difference between the most expensive case and the grid-supplied case is even less, a change of 0.7%.

4.2.2 Opportunistic Cases

Apart from the cases with fixed water purifying schedules it was also investigated how much water one could get from only surplus energy and at what cost. These opportunistic cases (carrying the case-IDs S1-WO-1 and S1-WO-2) are shown in Figure 4.9, which illustrates the significant potential of surplus energy for water purification. This originates from the low energy demand per cubic metre of purified water. Using all surplus energy to purify water in system set-up 1 and system set-up 2 would, on average, provide more than 10,000 litres and 20,000 litres per person per day, respectively.

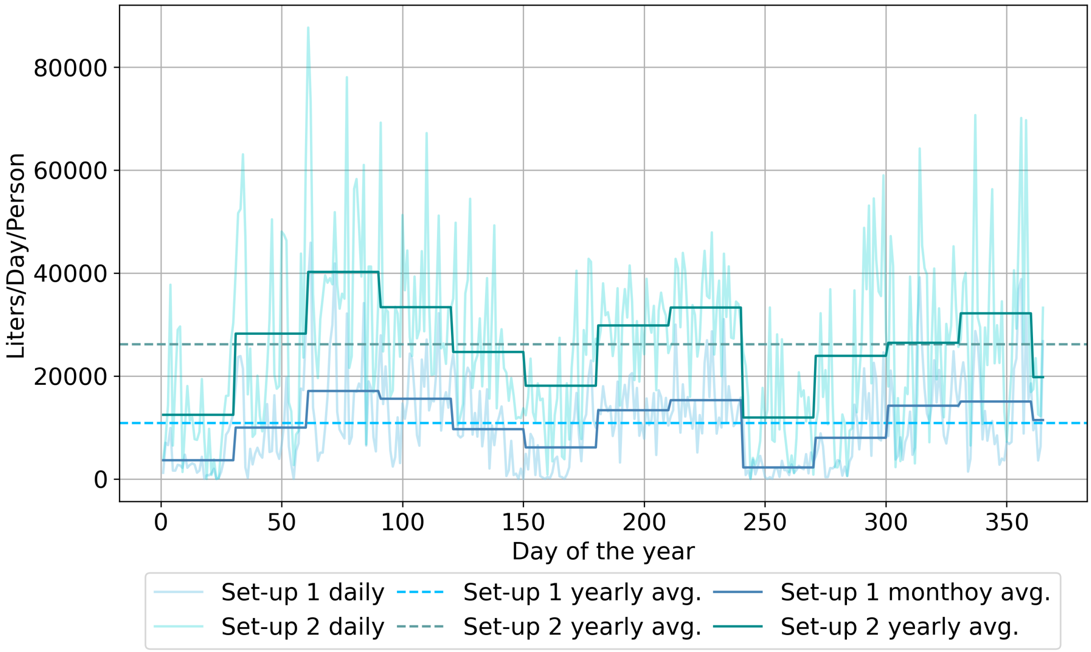


Figure 4.9: Available volume of purified water produced solely from surplus energy for system set-up 1 and system set-up 2 (cases S1-WO-1 and S1-WO-2). The figures shows both daily availability, monthly average availability per day and yearly average availability per day.

Even if the possibilities of using only surplus for water purification seem to be almost limitless, it is uncertain whether it is sufficiently available. The availability will be affected because excess energy is not available every hour. Figure 4.10 shows the modelled water output for different purification system capacities, based on the design assumptions described in the Method Chapter. This shows that a 100 l/day system is needed to achieve, on average, the same amount of water per person per day as with the 20-litre fixed schedules, and a 200 l/day system to achieve, on average, about the same amount of water per person per day as with the 50-litre fixed schedules.

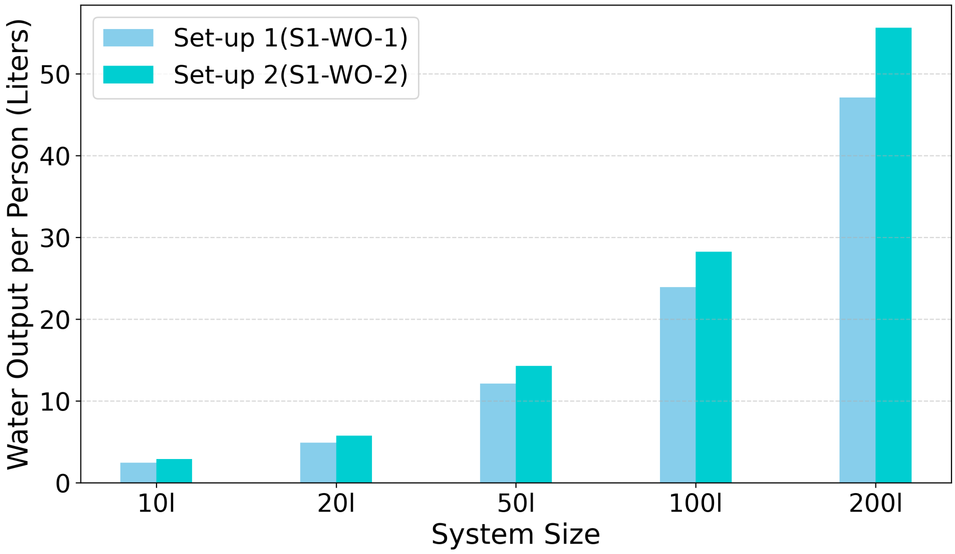


Figure 4.10: Volume of purified water output using only surplus energy for different purification system capacities.

Although surplus electricity is considered free, the UV disinfection system is associated with a cost related to its capacity. Figure 4.11 shows the marginal cost for the same output levels and system capacities. The marginal cost is higher compared to all the other cases including the grid option. This is the result of having a need of a higher capacity on the water purification plant and no constant or recurring availability.

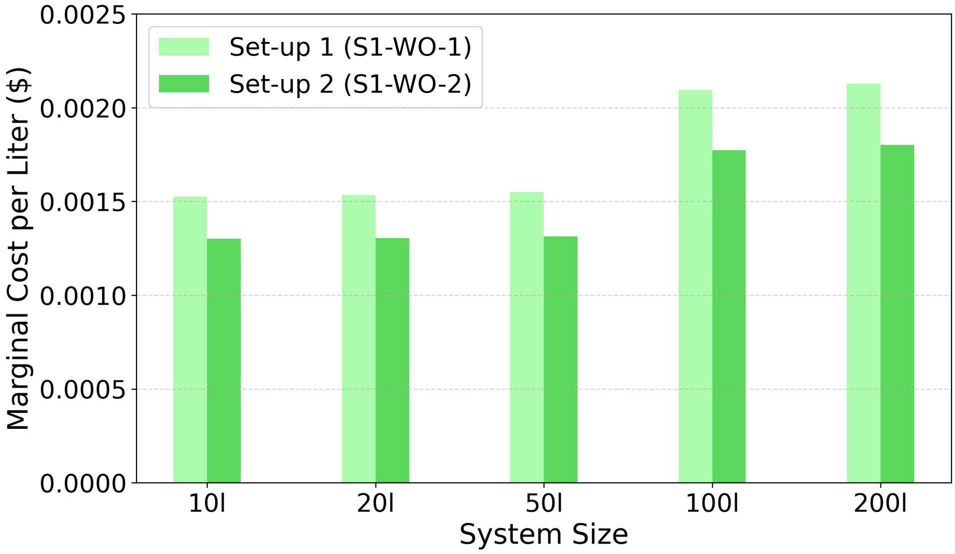


Figure 4.11: Marginal cost per litre of purified water based on opportunistic use of surplus energy at the different water purification system capacities.

4.3 Scenario 2 - Climate Change

This section presents the results from the Scenario modelling the impacts of climate change on energy demand and costs. It begins with showing the changes in water and energy needs across the three different climate change projections. This is followed by examining the implications on costs for a system designed to withstand these changes. Finally, the section ends by showing the impacts on system efficiency throughout the system's lifetime if a system is adapted to the different climate change projections.

4.3.1 Water & Energy Needs under Climate Change

Both the water requirement and the energy demand increase under the climate change Scenario. The increase in total net water requirement for the different cases (S2-W1.6-1, S2-W2.0-1, S2-W2.4-1), corresponding to a temperature increase of +1.6°C, +2.0°C and +2.4°C, is presented in 4.12. Similar to Scenario 0, the Base Case, the water requirement is not connected to any of the set-ups and the energy demand is shown for system set-up 1 but is representative for both as again, the difference summed over time is equal. The figure shows a pattern where the water requirement increases for each increase in temperature in most cases and most months. However, the water requirement decreases in March, April and May between case S2-W1.6 and S2-W2.0, and then again, increases for the case S2-W2.4. At most, the irrigation requirement increases about 60 m^3 per hectare for the case S2-W2.4 in January which is about a 7%, increase from Base Case that month.

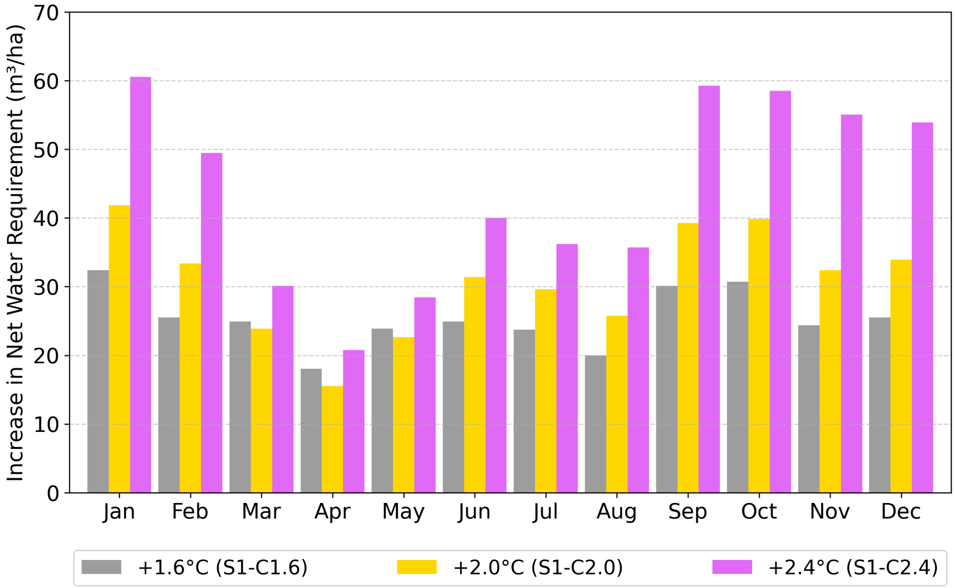


Figure 4.12: Increase in irrigation water requirement per hectare for different climate change cases with temperature increases of +1.6°C, +2.0°C, and +2.4°C for system set-up 1 (cases S2-W1.6-1, S2-W2.0-1, and S2-W2.4-1).

As the irrigation requirement increases, the energy demand for the system increases as well. The increase from the base case for the energy demand is presented in Figure 4.13. Similar to Figure 4.12, the highest increase is found in January for the case S2-C2.4, where the increase is about 68 kWh/ha/month compared to the Base Case, corresponding to a 16% increase.

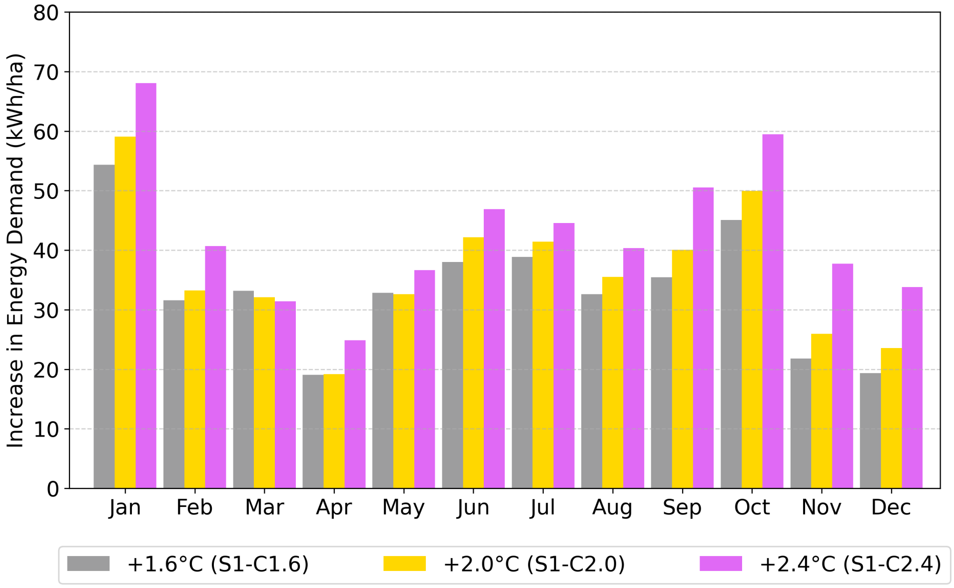


Figure 4.13: Increase in energy demand per hectare per month for different climate change cases with temperature increases of +1.6°C, +2.0°C, and +2.4°C for system set-up 1 (cases S2-C1.6-1, S2-C2.0-1, and S2-C2.4-1).

4.3.2 System Costs under Climate Change

An increase in demand means that a larger system is needed in order to meet the demand. In Figure 4.14, the increase in system cost for the different cases is shown. It shows the cost increase for both set-up 1 and set-up 2 as the temperature increases. The cost increases more overall for system set-up 2 in absolute values, however the increase in system cost is the same in percentage when comparing to the base cases S0-1 and S0-2. For the case S2-C1.6 the increase in cost is 3% for both set-ups, 4% for case S2-C2.0 for both set-ups and lastly about 6% for case S2-C2.4 for both set-ups.

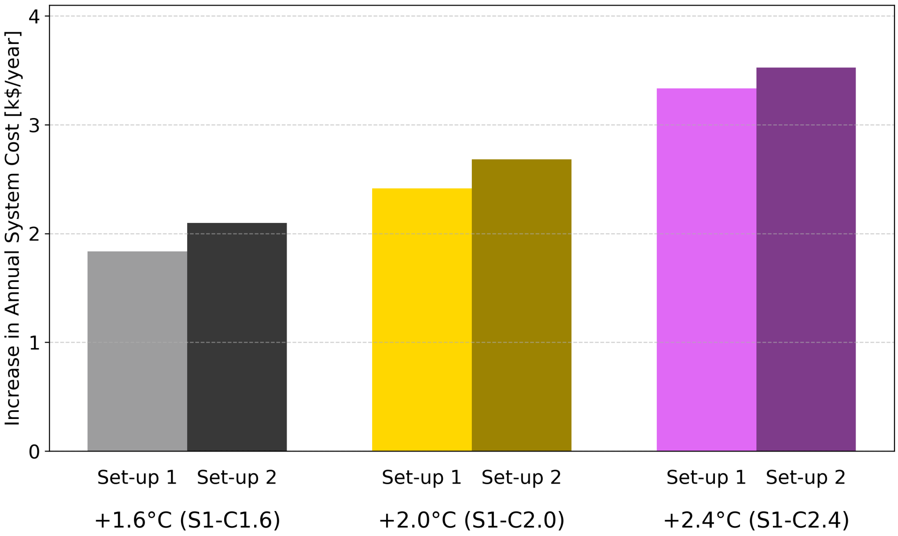


Figure 4.14: Increase in system cost for different climate change cases with temperature increases of +1.6°C, +2.0°C, and +2.4°C for system set-up 1 (cases S2-C1.6-1, S2-C2.0-1, S2-C2.4-1) and system set-up 2 (cases S2-C1.6-2, S2-C2.0-2, S2-C2.4-2).

4.3.3 System Efficiency under Climate Change

As a larger system is required to meet the increased irrigation requirement under future climate scenarios, more energy is also generated. If such a system, designed for the worst-case scenario (i.e. the S2-C2.4 case with a temperature increase of +2.4°C), is installed from the beginning, it will result in even more excess energy during the early years of operation, when demand is still lower. The excess energy will decrease over the years as demand increases due to climate change. This is illustrated in Figure 4.15, which shows the resulting excess energy for a system using the S2-C2.4 layout, along with the demands for both the base case (S0) and S2-C2.4. This is shown for both system set-up 1 and system set-up 2. The figure shows that excess energy decreases over time as demand grows. This is true for both system set-ups. The yearly pattern of excess energy follows the same trend for both set-ups, but as also shown in Figure 4.7 in the Base Case (S0), system set-up 2 has more overall excess energy. The total decrease in surplus energy caused by climate change is still much smaller than the remaining excess once the temperature has risen to +2.4°C, which the system was scaled for.

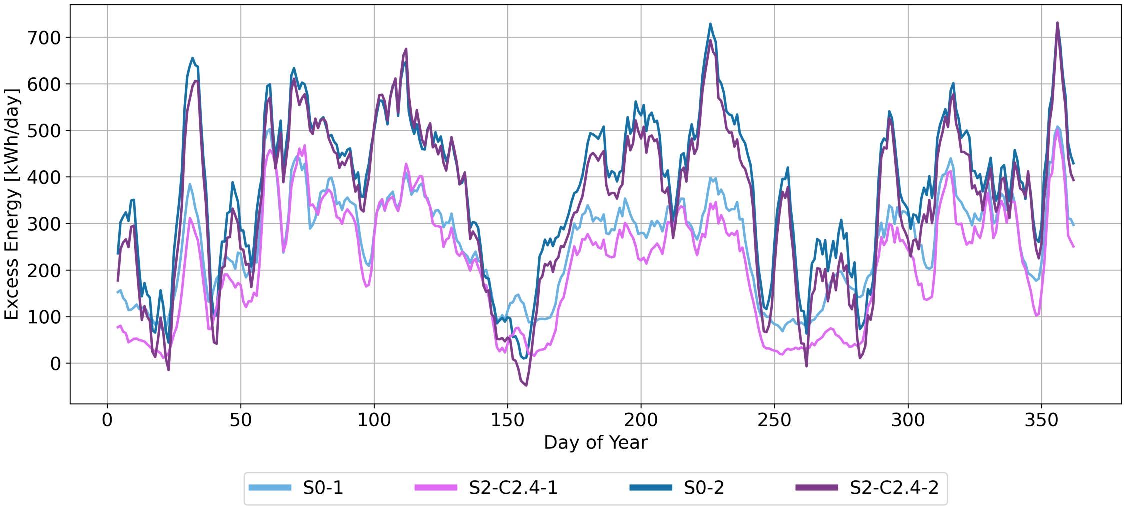


Figure 4.15: Excess energy over time for a system sized for the +2.4°C climate change case (case S2-C2.4) compared to the base case (S0), shown for both system set-up 1 and system set-up 2.

Climate change adaptation, through oversizing, will result in lower system efficiency. The amount of excess energy produced indicates both the system's efficiency and its potential to support other loads. Table 4.5 shows system efficiency for a system scaled to meet the demand of S2-C2.4 (i.e. with the supply from an S2-C2.4 system) but operating under different demand scenarios (S0, S2-C1.6, S2-C2.0 and S2-C2.4). The results show that system efficiency is more sensitive in system set-up 1 than in system set-up 2. Although system efficiency increases in both cases as demand rises, the increase is smaller for set-up 2. Notably, set-up 2 starts at 70%, just one percent below the Base Case (S0-2), and ends at 73%, which is two percent above it. Therefore, no significant change in system efficiency is observed for system set-up 2, as similar variations appear across scenarios when supply and demand are matched. In contrast, system set-up 1 shows a clearer change. The results suggest that system efficiency may be influenced by how demand develops with climate change, but that annual variability might play a bigger role than long-term shifts in total demand. Oversizing to adapt to climate change does affect efficiency, with a greater impact on set-up 1 than set-up 2.

Table 4.5: Long-term system efficiency for a system scaled to meet the demand under case S2-C2.4, evaluated against the demand levels of cases S0, S2-C1.6, S2-C2.0, and S2-C2.4, for both system set-up 1 and system set-up 2.

Case ID Demand	S2-C2.4-1 Supply	S2-C2.4-2 Supply
S0	76%	70%
S2-C1.6	79%	71%
S2-C2.0	80%	72%
S2-C2.4	81%	73%

4.4 Scenario 3 - Combined: Water Purification & Climate Change

The final section of this chapter presents the results for the combined Scenario. It first shows the cost of adaptation for a system addressing both the irrigation load and water purification under climate change. Then, the implications on performance without adaption are presented, highlighting the trade-offs between the two services for a system not designed to withstand climate change.

4.4.1 System Cost of Adaptation

For the Combined Scenario of the water purification and climate change projections, the annual costs are plotted in figure 4.16. The cost is shown for systems covering both the demand under the different climate change cases and the different fixed water purification schedules. It also shows the Base Cases (S0-1 and S0-2), some Scenario 1 cases without climate change (S1-W20d-1, S1-W20d-2, S1-W50d-1, S1-W50d-2) and some Scenario 2 cases without water purification (S2-C1-1.6-1, S2-C2.0-1, S2-C2.4-1, S2-C1-1.6-2, S2-C2.0-2, S2-C2.4-2). As many cases are plotted in this figure, their case IDs are shown on the bars, but the legend tries to help the reader better understand all combinations.

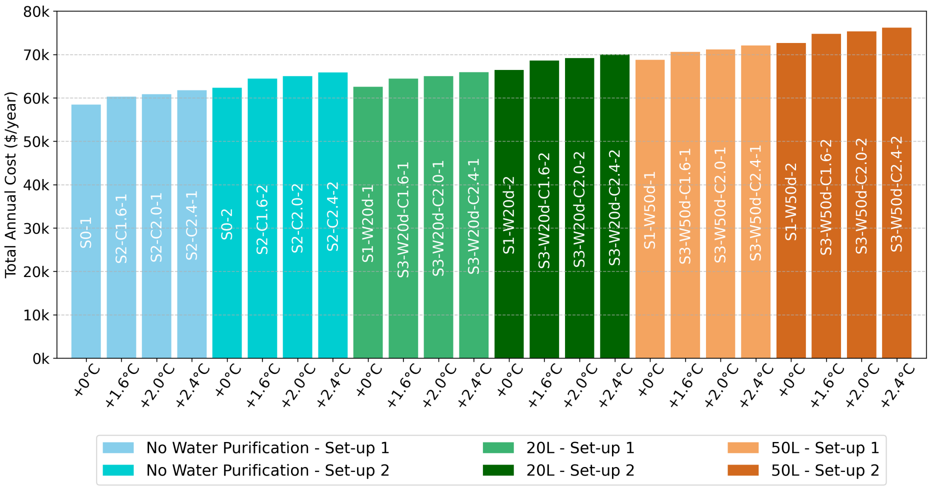


Figure 4.16: Annual system cost for the combined Scenarios, including both water purification (fixed schedules) and climate change projections, compared across all case combinations. Shown cases include: the Base Cases (S0-1 and S0-2), Scenario 1 cases without climate change (S1-W20d-1, S1-W20d-2, S1-W50d-1, S1-W50d-2), Scenario 2 cases without water purification (S2-C1.6-1, S2-C2.0-1, S2-C2.4-1, S2-C1.6-2, S2-C2.0-2, S2-C2.4-2), and Scenario 3 cases combining water purification and climate change (S3-W20d-C1.6-1, S3-W20d-C2.0-1, S3-W20d-C2.4-1, S3-W50d-C1.6-1, S3-W50d-C2.0-1, S3-W50d-C2.4-1, S3-W20d-C1.6-2, S3-W20d-C2.0-2, S3-W20d-C2.4-2, S3-W50d-C1.6-2, S3-W50d-C2.0-2, S3-W50d-C2.4-2).

The cost increases similarly to each of the scenarios separately, but to a higher extent since the demand for energy increases both due to the second load of water purification and climate change. The highest increase in cost is therefore, not surprisingly, the case purifying 50 litres of water per person per day under the climate projection where the temperature rises 2.4°C for system set-up 1 (i.e. case S3-W50d-C2.4-1). The cost for this case increases by 24% from the initial Base Case (S0-1). The corresponding number for system set-up 2 is an increase of 22%, showing no significant difference between the two system set-ups. From the results of the other scenario analyses it can be deduced that the highest contribution to the cost increase comes from the water purification, as the increase in cost for the different cases in the water purification scenarios are higher (maximum 19%) than the cost increase under the different climate change cases (maximum 6%).

4.4.2 Performance Without Adaptation

The Combined Scenario was also analysed from another perspective, examining how both irrigation and water purification demands could be met under a system that is not scaled to withstand climate change. Table 4.6 presents the results for fulfilling both irrigation and water purification demands using different prioritisation strategies under the climate change case corresponding to a +2.4°C increase in average temperature for system set-up 1 (i.e., case S2-C2.4-1). The investigated cases include S3-W20c-C2.4-1, S3-W20d-C2.4-1, S3-W50c-C2.4-1, and S3-W50d-C2.4-1.

Table 4.6: System performance under climate change case S2-C2.4 with undersized system capacity, comparing irrigation-prioritised and water purification–prioritised operations. Shown for each case are the achieved irrigation coverage and water purification coverage, along with the change in coverage (Δ) when shifting operational priority.

	Irrigation Prioritised		**Water Purification Prioritised**			
Case ID	**Irrigation Coverage**	**Purifying Water Coverage**	**Irrigation Coverage**	**Purifying Water Coverage**	**ΔIrrig.**	**ΔPurif.**
S3-W20c-C2.4-1	97%	64%	97%	100%	0%	**+36%**
S3-W20d-C2.4-1	97%	30%	97%	100%	0%	**+70%**
S3-W50c-C2.4-1	97%	65%	97%	100%	0%	**+35%**
S3-W50d-C2.4-1	97%	30%	97%	100%	0%	**+70%**

This analysis reveals that an irrigation-prioritised strategy achieves 97% of the irrigation energy demand but only 65% and 30% of the water purification demand for the constant and daily cases, respectively. The difference in demand coverage between 20 and 50 litres of purified water per day per person is minimal. However, with a strategy prioritising water purification, the system maintains 97% coverage of irrigation demand while fully meeting the water purification demand. This results in a 35% or 70% increase in demand fulfilment for constant or daily flow, respectively, compared to the strategy prioritising irrigation first, without affecting the irrigation demand coverage. This is likely due to the different characteristics of the loads.

While the irrigation energy demand is substantial compared to the water purification demand, it is flexible in terms of the time of day when the water is pumped. Therefore, prioritising the water purification load over the irrigation load does not significantly reduce the energy available for irrigation, because the irrigation load affected by prioritising water purification is small and can be shifted to another hour without affecting overall irrigation.

5

Discussion

This chapter discusses the results from the different scenarios, interprets them and extends beyond a simple presentation of the numbers from running the model. First, the implications of the results will be addressed, then the value of bio-diesel as a controllable energy source, water access, and sustainability more broadly is discussed. Lastly, a reflection on ethical considerations and future work is presented.

5.1 Implications of the Results

The results suggest that both system set-ups can successfully meet the irrigation demand, but they come with distinct trade-offs in terms of cost, operational flexibility, system efficiency and possibilities for supporting a second load apart from irrigation. Although set-up 1 is more cost-effective and efficient, set-up 2 offers greater possibilities when it comes to utilizing surplus energy. This difference highlights an important trade-off between system capacity on the one hand and cost and efficiency on the other. These findings have broader applicability beyond the case study because the underlying challenges and trade-offs are not unique to the village of Tabagwe. Many agricultural communities in Sub-Saharan Africa, and other regions with similar climate and socio-economic conditions, face comparable challenges and possibilities. Similar challenges such as limited or unreliable grid infrastructure, especially in rural and remote areas, low rates of modern irrigation technologies leading to dependence on erratic rainfall and financial barriers to adopting new technology. Similar opportunities such as high solar irradiance and long daylight hours, making solar-powered systems viable, growing access to decentralized renewable off-grid systems and substantial potential in productivity gains from introducing modern irrigation systems. In such contexts these systems offer a promising approach to meet the demand, either powered by solar PVs and backup generation, or solar alone. The latter, however, requires a larger system capacity, which comes at a higher cost. The irrigation system can also be integrated with a load representing a service of water purification, however at a price of either higher system cost or inferior availability of the clean water service. Additionally, the energy demand for irrigation is likely to increase over its lifetime due to climate change, particularly if the system is located in the sub-Saharan region. This trend, however, may not be applicable globally, as the impacts of climate change vary significantly by region. Especially regarding changes in rainfall patterns, which strongly influence the irrigation need.

5.2 Evaluation of the Method

When developing a model, the end-product is always just an attempt to describe reality. It includes both limitations and simplifications of a complex world. Therefore, it is important to point out when and to what extent the model is valid as well as which conclusions can be drawn from the model's output. The energy system model developed is based on a simplified soil moisture balance where daily irrigation requirements are calculated from evapotranspiration, and effective rainfall is not accounted for if more rain than needed comes. That means, if a substantial amount of rain falls in one day, it will not affect next day's irrigation requirement. This leads to an overestimation of irrigation requirement since excess water is not calculated into the balance of moisture in the soil. Furthermore, the decision to apply the highest crop coefficients throughout the entire cultivation period introduces an additional conservative element to the model. This worst-case approach ensures that the estimated irrigation requirement is likely to be somewhat higher than the actual one. As a consequence, if a system design is based on these results it should be at least sufficiently large. Another important aspect to consider is the choices made for the preprocessing steps for the irrigation demand. For instance, even if the choice of when to cultivate what is based on common practices in the region considered in the case study, if other choices were to be made the results might change drastically. For instance, as neither maize or beans are cultivated in July or August, as can be seen in 4.2, the irrigation requirements are not overly high in those months. However, as it can be seen that the need for irrigation for bananas is higher than most months, indicating that these months likely would have higher requirements if maize and beans were also chosen to be cultivated during these months. Next, only four years of weather data are used when preprocessing the input vectors, which might lead to too high or too low values if extreme events occurred during these years.

The costs used in the model are highly based on general values which might alter locally to a high extent. Different economic policies might also affect. Uncertainties in cost data might lead to significant choices by the model that might not always hold and the system could look different with other numbers. One example is if the battery cost would be decreased, then the solar-only based system might have installed in batteries before such a high capacity in only solar which would impact the operation of the system, its efficiency and possibility for utilization of the surplus. Other factors that impact are the CRF and the lifetime of the technologies. If a technology has a shorter lifetime the CRF gets higher, leading to a higher annual cost and at the same time impacting the cost distribution.

5.3 Value and role of bio-diesel as backup generation

Even though the inclusion of bio-diesel in set-up 1 ensures a more effective and economic system, the sustainability and feasibility of this option can be questioned. Currently, there is no bio-diesel infrastructure in Tabagwe, and such systems are not yet established in Rwanda. This raises concerns about the realism of relying on bio-diesel as an energy source in the short term. However, from a performance perspective, incorporating bio-diesel generators improves system efficiency, not only in terms of energy but also cost. In drought years, when irrigation water requirement increases, the bio-diesel system offers valuable flexibility. Since it is controllable, it can be used more intensively to meet demand, even if it comes at the cost of additional fuel. This flexibility strengthens the system's resilience to changing demands. In contrast, system set-up 2 solely relying on solar lacks this flexibility. Even if reduced rainfall, as probable in the situation of drought, could correlate with increased solar irradiance due to fewer clouds, it remains uncertain whether the increase in solar output would be sufficient to meet the higher irrigation requirements. However, a drought will likely reduce the available water at the source, which could result in unmet irrigation requirements due to water scarcity, even if the additional energy demand can still be satisfied.

Diesel generators are widely used across Sub-Saharan Africa as backup power sources and are compatible with both fossil diesel and bio-diesel. This compatibility suggests that local capacity for operation and maintenance already exists, which supports technical feasibility. At the same time, the fact that the generator considered can run on a fossil energy source also poses a sustainability risk. The lower cost and higher availability of fossil diesel might lead operators to switch fuels, undermining the climate benefits that justify bio-diesel in the first place. This raises another concern about whether the flexibility and resilience of the system may come at the cost of long-term sustainability. The availability of bio-diesel also includes uncertainties. Even if bio-diesel becomes more available in the region in the future, economic fluctuations could lead to supply shortages, causing a risk for the reliability of the system. This again raises concerns about switching to the use of fossil diesel undermining the sustainability of the system. Furthermore, building a significantly oversized system, as in set-up 2, may also be questionable from both sustainability aspects and an economic point of view. Overall, when comparing a system with a bio-diesel option and one without, the value of bio-diesel shines clearly, but not without important concerns. In essence, the balance between flexibility, resilience and reliability is key to achieving a system which is both feasible in the short term and sustainable in the long term.

5.4 Water access and competing needs

The question about how to prioritise water usage becomes critical considering the water purification scenario, particularly in situations of limited water availability. While this thesis focuses on the electrified irrigation system as the primary service, and examines to what extent such system can also support water purification loads, it is essential to consider the implications these might have on water allocation. Irrigation typically requires significant more water than other uses, such as domestic consumption or electricity generation. If water purification is treated as just a side benefit of the irrigation system, clean drinking water may risk being perceived as something less important than agricultural productivity. However, as the results of section 4.2 and especially figure 4.8, show that water purification powered by an electrified irrigation system can be more cost-effective than relying on the grid. This means more people could potentially benefit from clean water, as the volume of the purified water per unit of invested capital is higher in the integrated system. This highlights a synergy between irrigation and water purification. However, to optimise both outputs the best strategy might not be to prioritise irrigation every time as seen in the results for the combined scenario in section 4.4. In fact, prioritising water purification over irrigation allows both demands to almost be met even if the system is undersized. This points to the need for flexible strategies in water allocation based on current needs.

Another layer of complexity arises from political and geographical considerations. The Kaborogota River, assumed to be the source for both irrigation and purification in this case study, flows downstream from Uganda into Rwanda. This cross-border dependency introduces the risk of water conflict, especially if the governing bodies of the two countries have different views on water usage. While conflict risk is low during times of water abundance, it can become critical in periods of scarcity. This is an increasingly likely scenario, as the climate change results indicate a rise in drought frequency. The issue of freshwater allocation is not unique to Tabagwe village. History and current events show that water related tensions are widespread and governance are essential not only for system efficiency and equitable access, but also for long term regional stability.

5.5 Infrastructure, lifecycle and material concerns

Another sustainability aspect is regarding the UV lamps used for water purification. Since these require replacement each and every year, they might be a cause for unsustainability. Without a system in place for proper collection and recycling, they pose a risk of environmental and social harm. As explained in the Theory chapter, UV lamps often contain mercury, a toxic heavy metal, and if improperly disposed of, they could lead to contamination of, for instance, the freshwater they are supposed to purify. This highlights a critical aspect of establishing systems for lifecycle management. Technologies that rely on frequent replacement of components containing toxic chemicals have the need for structure and governance which can assure safe handling and disposal. This puts high pressure on the local community and likely requires support or intervention from higher levels of governance or authority. Without structures for end-of-life stage, even if the system work well and sustainable in operation, delivering a clean service, the results might lead to harmful outcomes in the long run. Furthermore, establishing a maintenance and supply chain system, particularly in rural areas, require careful planning and resilient societies free from corruption. Things that are vital in order to establish good access to spare parts, trained technicians and waste management infrastructure. The same lifecycle considerations apply to the solar PVs, batteries, and pumps in the system. Many of these technologies include components with, or are manufactured, using both rare earth metals and conflict metals, contributing to environmental and geopolitical challenges. Rare earth metals, such as neodymium, are, for instance, often used in electric motors and are currently mined only in few countries. Further on, conflict metals, like cobalt, tin or tungsten, are often found in lithium-ion batteries. These metals are often mined in regions deeply burdened by poor labour conditions and ongoing conflicts which might raise ethical questions and thereby complicate the aim for sustainability in a broad meaning even further. Ultimately, this emphasizes the end-of-life disposal and recycling as important parts that should be viewed as integral to the planning in order to ensure a sustainable system throughout the whole lifetime of the system.

5.6 Climate Change Uncertainties

In the context of climate change, the electrified irrigation system needs to be designed to withstand increasing temperatures and shifting rainfall patterns. The results showed that irrigation requirement and therefore also the energy demand increase with higher temperature projections. This underscores the importance of planning for a more robust system that can fulfil its purpose in a reliable way across its expected lifetime. However, as climate is a highly complex system, projections always come with uncertainties. In the climate change scenario, only two parameters, temperature and precipitation, were changed for the different cases. The temperature was modelled using the IPCC climate projections of how the global average surface temperature might increase although these might not apply locally in Tabagwe. Similarly, even if the precipitation was modelled based on more regional projections, rainfall remains a highly local and variable phenomenon impacted by several parameters in the Earth's systems. Naturally, the value of these results lies more in the direction of change than in the precise figures. The results indicate a trend towards increased water and energy demand, suggesting a larger, more expensive system if it is going to withstand climate change. If the system is not sized with climate change in mind; meaning that it is undersized, the impact could correspond to the results of section 4.4 which shows the result of the combined scenario. When a 2.4°C increase in temperature is applied to a system designed for current conditions, resulting in a 3% deficit in meeting irrigation energy demand. While seemingly small, this shortfall could have significant consequences if it occurs during the development phase of the crop growth, potentially leading to yield loss, income reduction and food insecurity. These risks highlight a vulnerability in the system, potentially leading to devastating consequences.

Moreover, the need for larger systems under climate change introduces another layer of trade-offs. A system sized for future climate projections may appear inefficient at first, with notable energy excess in the early years. However, this excess can be viewed either as a wasted resource or as a potential opportunity, for instance for water purification, examined in this thesis, but also for additional services like household electrification, small enterprises or other income generating activities. It could then provide a broader development side effect. This reflects a systems thinking approach where climate adaptation can overlap with sustainable development in a rural setting. This approach might also meet criticism as the excess energy is reduced along the lifetime of the system. Therefore, it is important to put effort in various ways at the same time and avoid creating unsustainable dependency for the community. However, as development does not happen overnight, utilizing the synergies between electrified irrigation and other side benefits can be a step along the way.

Ultimately, designing climate-resilient infrastructure is not just a technical challenge but also a question of strategic prioritisation and long-term thinking, which is touched upon in section 5.4. It requires balancing cost, sustainability, and flexibility under uncertainty. Integrating climate projections into the early planning stages is therefore essential, not just to protect agricultural productivity, but to ensure that water and energy infrastructure remains reliable and effective in a changing climate.

5.7 What Does Sustainable Really Mean?

In the light of the results and a discussion focusing on the two different model setups, the scenarios and their implications, a broader question regarding sustainability comes up: when does a system become sustainable? And sustainable in terms of what? There might be conflicting interests in achieving for instance economic sustainability and environmental sustainability. As discussed previously, the use of bio-diesel might be questionable due to its lack of availability and risk of substitution with fossil diesel. On the other hand, building a significantly oversized solar system to eliminate the risk of using fossil energy sources may also be questionable from a sustainability standpoint. An oversized system may underutilize materials and increase embodied emissions from extraction and production stages without proportional benefit. An oversized solar panel system also means that a larger land area is needed for the installation which might be problematic if placed on arable land, potentially competing with agriculture.

Furthermore, underutilization of system components reduces efficiency in terms of both cost and resource use. This reflects a sustainability dilemma, choosing between a system that is lean and efficient today and one that is resilient and prepared for future uncertainties but oversized. Alternatively, one could also choose to utilize the inefficiencies for other productive uses, again potentially contributing to broader development outcomes. True sustainability may lie in finding both balance and creativity in utilization. A system that is adaptable, minimizes negative externalities, and considers not only how each individual component performs separately, but how the system as a whole maximizes benefits while minimizing harm, is ideal. Lifecycle impacts and system feedback loops need to be considered holistically in order to support long term development in a meaningful and responsible way.

5.8 Positionality and Ethical Considerations

While the previous two sections discussed structural and societal dimensions, this one turns inwards, toward the role of the researcher and the ethical complexities of working in a new context and culture that is not my own. As someone who is neither Rwandan nor African, it is valid to question the appropriateness of conducting a case study in Rwanda without deep contextual knowledge about Tabagwe. Although this thesis approaches the subject from a technical energy systems perspective, it is inherently multidisciplinary, as it engages with fields such as agriculture and water management. These are parts that are central to the research but where I lack a solid academic background. This brings up the importance of ethical considerations, particularly the risk of imposing assumptions that may not align with local realities or priorities. Conducting research in a geographical and cultural context unfamiliar to the researcher comes with limitations in understanding the nuanced social and cultural dynamics as well as risks of misinterpreting how things actually work. Recognizing these limitations and risks is of high importance. Throughout the process, I have aimed to maintain transparency and avoid making unjustified assumptions in order not to oversimplify anything of importance. The intention is to contribute technical insights that, at best, could support future work and to advocate global collaborations grounded in mutual respect and shared learning.

In light of this reflection, ethical and positional awareness is in itself not the limitation but rather necessary in order to critically review one's own understanding, and conduct responsible research. When coming from a foreign country to conduct research or implement new technical systems, it is important to approach the work thoughtfully to avoid causing harm. Important considerations include local involvement and ownership, respect for local knowledge and culture, capacity building and skill transfer, transparency, environmental, social and economic sustainability, informed consent, fair compensation for labour and ensuring long-term responsibility.

5.9 Future Work

Given the complexity of the systems studied, future research could deepen understanding of how renewable energy can support agricultural water management while balancing trade-offs. Opportunities exist to explore alternative crop selection and cultivation schedules, incorporate fluctuating water availability, assess multiple irrigation systems, and achieve a more comprehensive integration of climate change effects. Investigating these directions could improve the robustness and applicability of these findings to support sustainable agricultural development.

One important area for future research relates to assumptions about the crops cultivated, which significantly influenced the results. Future studies could explore alternative cultivation schedules and include a wider variety of crops beyond the three most commonly cultivated. Such research would help better understand how different crop choices impact water and energy demand. For example, investigating cultivation during season C beyond bananas could reveal opportunities to increase farmer income. Expanding the crop selection to include crops of higher market value could also improve the economic viability of these electrified irrigation systems.

The availability of the water resource, assumed to be the Kaborogota River in Tabagwe, was considered to be constant and unconstrained throughout this study. In reality, variations in drought and rainfall can significantly influence water availability and its capacity to support irrigation services. Future research could include fluctuations in river flow to better reflect real conditions. This would require hydrological data over time and would allow for an assessment of potential environmental impacts further downstream along the river. For instance, future studies could examine how the system might affect downstream availability and how the electrified irrigation system would perform during periods of scarcity.

Furthermore, it would be valuable to explore other irrigation systems, as their efficiency and energy consumption can vary significantly. Drip irrigation systems generally demonstrate higher water-use efficiency than, for instance, sprinkler systems. However, drip irrigation systems may require different maintenance procedures, such as periodic cleaning of plumbing components, which this thesis does not address. Exploring these alternatives could reveal trade-offs between water use efficiency, energy demand, and system complexity. A better understanding of how these irrigation technologies interact with renewable energy supply would enhance the applicability of the systems studied under varying agricultural conditions.

Regarding the additional load of water purification, it would be valuable to investigate other types of electrical loads with varying characteristics. Since the water purification load is very small but inflexible, at least in the fixed schedule cases investigated, exploring a broader range of flexible and inflexible loads could provide insights into how the electrified irrigation system might support broader electrification. For example, loads such as electricity for households or for productive use, with varying energy demand profiles and flexibility, could be investigated to further understand which loads are compatible with renewable energy and how they integrate with irrigation systems. Understanding how these different loads interact could help optimise system sizing and further explore synergies between renewable energy and other types of loads. Future research in this area could contribute to developing integrated systems that better meet the needs of the community and enhance development on a broader scale.

The climate change scenario considered in this thesis altered only two parameters, global average temperature increase and precipitation change in East Africa. Future work could benefit from a more comprehensive climate modelling approach that incorporates a wider range of climate variables and cases. This would provide a more robust assessment of how climate change might affect electrified irrigation. The inclusion of extreme weather events, such as long periods of drought, would give another perspective on the impacts on food production systems under climate change. Such detailed modelling could improve the understanding of system resilience and support more informed adaptation strategies under more complex and realistic climate futures.

6

Conclusion

This report has explored how renewable energy systems can support water management through linear optimization in rural Sub-Saharan Africa by examining a case study in Tabagwe, Rwanda. The findings show that the energy demand of electrified irrigation varies depending on crop type and season, but requires on average 340 kWh/ha/month. To meet this demand sustainably and cost-effectively, most capacity should be invested in solar photovoltaics. The results indicated that investments in battery storage do not support a cost-effective solution if the load only includes water pumping for irrigation. Integrating a bio-diesel generator can enhance flexibility and reduce costs, although concerns about fuel availability and long-term sustainability remain.

Electrified irrigation systems can also support water purification through UV disinfection, with lower marginal cost per litre of water compared to grid-supplied alternatives. The results also showed a lower marginal cost per litre of water through integrated systems compared to separate. This represents a promising synergy between agricultural and domestic water systems. Prioritizing water purification within the energy management strategy appears to be the most effective approach for ensuring a higher delivery and performance of the systems, especially if the systems are not adapted to climate change from the start.

Climate change is expected to increase both energy demands and system costs. However, oversized systems might provide opportunities to support broader electrification goals. Overall, aligning system operation with local needs can strengthen resilience, support productive agriculture, and improve access to clean drinking water in similar settings.

Bibliography

[1] United Nations, *Transforming our world: The 2030 agenda for sustainable development,* 2015, `https://sdgs.un.org/2030agenda`, Accessed: 2025-05-06.

[2] C. Kimberly Mullen, *Information on earth's water,* n.d, `https://www.ngwa.org/what-is-groundwater/About-groundwater/information-on-earths-water`, Accessed: 2025-05-16.

[3] Organisation for Economic Co-operation and Development, *Water and agriculture*, Accessed: 13 May 2025, 2025. [Online]. Available: `https://www.oecd.org/en/topics/water-and-agriculture.html`.

[4] A. T. Gashaye, H. Liu, and J. Li, "The effect of access to electricity on rural households of underdeveloped countries: Evidence from ethiopia," *Energy Policy*, vol. 199, p. 114 531, 2025, ISSN: 0301-4215. DOI: `10.1016/j.enpol.2025.114531`.

[5] J. Quispe, A. Obispo, and F. Alcantara, "Economic feasibility assessment of microgrids with renewable energy sources in peruvian rural areas," *Clean Technologies and Environmental Policy*, vol. 26, pp. 1415–1438, 2024. DOI: `10.1007/s10098-023-02463-w`.

[6] I. Bisaga, P. Parikh, J. Tomei, and L. To, "Mapping synergies and trade-offs between energy and the sustainable development goals: A case study of off-grid solar energy in rwanda," *Energy Policy*, vol. 149, Nov. 2020. DOI: `10.1016/j.enpol.2020.112028`.

[7] F. Lombardi, F. Riva, M. Sacchi, and E. Colombo, "Enabling combined access to electricity and clean cooking with pv-microgrids: New evidences from a high-resolution model of cooking loads," *Energy for Sustainable Development*, vol. 49, pp. 78–88, 2019, ISSN: 0973-0826. DOI: `10.1016/j.esd.2019.01.005`.

[8] A. Chandra, D. M. Heeren, L. Odhiambo, and N. Brozović, "Water-energy-food linkages in community smallholder irrigation schemes: Center pivot irrigation in rwanda," *Agricultural Water Management*, vol. 289, p. 108 506, 2023, ISSN: 0378-3774. DOI: `10.1016/j.agwat.2023.108506`.

[9] P. Waller and M. Yitayew, *Irrigation and Drainage Engineering.* Cham, Switzerland: Springer International Publishing, 2016, ISBN: 978-3-319-05698-2. DOI: `10.1007/978-3-319-05699-9`.

[10] J. De Trincheria *et al.*, "Fostering the use of rainwater for small-scale irrigation in sub-saharan africa," Hamburg University of Applied Sciences, Hamburg, Germany, Technical Report, 2016, AFRHINET Project. Financed by ACP-EU Cooperation Programme in Science and Technology (ACP-S&T II). DOI: `10.13140/RG.2.2.11049.39522`.

[11] Intergovernmental Panel on Climate Change, “Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,” Intergovernmental Panel on Climate Change, Geneva, Switzerland, Tech. Rep., 2023, p. 184. DOI: `10.59327/IPCC/AR6-9789291691647`.

[12] World Meteorological Organization (WMO), “State of the global climate 2024,” Geneva, Switzerland, Tech. Rep. WMO-No. 1368, 2025, p. 42. [Online]. Available: `https://library.wmo.int/records/item/69455-state-of-the-global-climate-2024`.

[13] Rwanda Energy Group, “Annual report 2023–2024 fiscal year,” Rwanda Energy Group, 2024, Accessed: 2025-05-19. [Online]. Available: `https://www.reg.rw/fileadmin/user_upload/REG_Annual_Report_2023-24FY.pdf`.

[14] Rwanda Development Board, *Renewable energy*, Accessed: 2025-05-19, 2024. [Online]. Available: `https://rdb.rw/renewable-enrgy/`.

[15] P. Behuria, “Ban the (plastic) bag? explaining variation in the implementation of plastic bag bans in rwanda, kenya and uganda,” *Environment and Planning C: Politics and Space*, vol. 39, no. 8, pp. 1791–1808, 2021. DOI: `10.1177/2399654421994836`.

[16] Republic of Rwanda, “Updated nationally determined contribution (ndc) of rwanda,” United Nations Framework Convention on Climate Change (UNFCCC), Tech. Rep., May 2020, Accessed: 2025-05-18. [Online]. Available: `https://unfccc.int/sites/default/files/NDC/2022-06/Rwanda_Updated_NDC_May_2020.pdf`.

[17] Ministry of Agriculture and Animal Resources, Republic of Rwanda, “Rwanda irrigation master plan,” Ministry of Agriculture and Animal Resources, Republic of Rwanda, Tech. Rep., 2018, Accessed: 2025-05-19. [Online]. Available: `https://www.minagri.gov.rw/fileadmin/user_upload/Minagri/Publications/Policies_and_strategies/Rwanda_Irrigation_Master_Plan.pdf`.

[18] National Institute of Statistics of Rwanda. “Labour force survey annual report 2023.” Accessed: 2025-01-04. (2023), [Online]. Available: `https://www.statistics.gov.rw/publication/2162`.

[19] Ministry of Agriculture and Animal Resources (MINAGRI), *Rwanda irrigation master plan*, Accessed: 2025-01-06, 2020. [Online]. Available: `https://www.minagri.gov.rw/fileadmin/user_upload/Minagri/Publications/Policies_and_strategies/Rwanda_Irrigation_Master_Plan.pdf`.

[20] Google. “Location of tabagwe.” Accessed: 2024-11-03. (2024), [Online]. Available: `https://maps.app.goo.gl/1CWmBC3t3tQXo7ZKA`.

[21] National Institute of Statistics of Rwanda (NISR), “Seasonal agricultural survey, annual report,” National Institute of Statistics of Rwanda (NISR), P.O Box 6139, Kigali, Rwanda, Dec. 2024. [Online]. Available: `https://www.statistics.gov.rw/datasource/205`.

[22] National Institute of Statistics of Rwanda (NISR), “Seasonal Agricultural Survey, Annual Report, December 2024,” National Institute of Statistics of Rwanda, Kigali, Rwanda, Tech. Rep., 2024. [Online]. Available: `https://www.statistics.gov.rw`.

[23] National Institute of Statistics of Rwanda (NISR), *The fifth rwanda population and housing census (rphc2022)*, Field work conducted from August 16 to 30, 2022, P.O. Box 6139, Kigali, Rwanda, 2022. [Online]. Available: `http://www.statistics.gov.rw`.

[24] Allen, R.G., Pereira, L.S., Raes, D., Smith, M., "Crop evapotranspiration - guidelines for computing crop water requirements - fao irrigation and drainage paper 56.," *NO*, 1998.

[25] S.-F. Kuo, B.-J. Lin, and H.-J. Shieh, "CROPWAT model to evaluate crop water requirements in taiwan," in *1st Asian Regional Conference, International Commission on Irrigation and Drainage*, Seoul, South Korea, 2001.

[26] International Energy Agency (IEA), "Renewables 2022 – analysis and forecast to 2027," International Energy Agency, 2022, Accessed: 2025-05-20. [Online]. Available: `https://iea.blob.core.windows.net/assets/ada7af90-e280-46c4-a577-df2e4fb44254/Renewables2022.pdf`.

[27] S. Panagoda *et al.*, "Advancements in photovoltaic (pv) technology for solar energy generation," vol. 43, pp. 30–72, Jul. 2023, Accessed: 2025-05-09. [Online]. Available: `https://www.researchgate.net/publication/372364724_Advancements_In_Photovoltaic_Pv_Technology_for_Solar_Energy_Generation`.

[28] W. Osman *et al.*, "Comparative review of biodiesel production and purification," *Carbon Capture Science & Technology*, vol. 13, p. 100 264, 2024, ISSN: 2772-6568. DOI: `10.1016/j.ccst.2024.100264`.

[29] J. Tebbe *et al.*, "Innovations and prognostics in battery degradation and longevity for energy storage systems," *Journal of Energy Storage*, vol. 114, p. 115 724, 2025, ISSN: 2352-152X. DOI: `10.1016/j.est.2025.115724`.

[30] J. Qu, Z. Jiang, and J. Zhang, "Investigation on lithium-ion battery degradation induced by combined effect of current rate and operating temperature during fast charging," *Journal of Energy Storage*, vol. 52, p. 104 811, 2022, ISSN: 2352-152X. DOI: `10.1016/j.est.2022.104811`.

[31] S. Dominika, F. Wiesław, P. Andrzej, J. Grzegorz, and Ł. Bąk, "Analysis of the ecological footprint from the extraction and processing of materials in the lca phase of lithium-ion batteries," *Sustainability*, vol. 16, no. 12, 2024, ISSN: 2071-1050. DOI: `10.3390/su16125005`.

[32] L. G. Swan and P. L. Allen, "Integrated solar pump design incorporating a brushless dc motor for use in a solar heating system," *Renewable Energy*, vol. 35, no. 9, pp. 2015–2026, 2010, ISSN: 0960-1481. DOI: `10.1016/j.renene.2010.02.002`.

[33] V. Buono da Silva Baptista, J. Córcoles, A. Colombo, and M. Moreno, "Feasibility of the use of variable speed drives in center pivot systems installed in plots with variable topography," *Water*, vol. 11, p. 2192, Oct. 2019. DOI: `10.3390/w11102192`.

[34] A. Schmalwieser, G. Hirschmann, A. Cabaj, and R. Sommer, "Method to determine the power efficiency of uv disinfection plants and its application to low pressure plants for drinking water," *Water Science and Technology: Water Supply*, vol. 17, Dec. 2016. DOI: `10.2166/ws.2016.185`.

[35] F. Reygadas, J. S. Gruber, I. Ray, and K. L. Nelson, “Field efficacy evaluation and post-treatment contamination risk assessment of an ultraviolet disinfection and safe storage system,” *Water Research*, vol. 85, pp. 74–84, 2015, ISSN: 0043-1354. DOI: `10.1016/j.watres.2015.08.013`.

[36] R. Pizzichetti *et al.*, “Environmental life cycle assessment of uv-c leds vs. mercury lamps and oxidant selection for diclofenac degradation,” *Sustainable Materials and Technologies*, vol. 41, e01002, 2024, ISSN: 2214-9937. DOI: `10.1016/j.susmat.2024.e01002`.

[37] N. Voutchkov, “Energy use for membrane seawater desalination – current status and trends,” *Desalination*, vol. 431, pp. 2–14, 2018, "Desalination, energy and the environment" in honor of Professor Raphael Semiat, ISSN: 0011-9164. DOI: `/10.1016/j.desal.2017.10.033`.

[38] A. A. Ali, O. T. Iorhemen, and R. W. Thring, “Climate adaptation and resilience of biofiltration as a low-cost technological solution for water treatment – a critical review,” *Cleaner Water*, vol. 3, p. 100 062, 2025, ISSN: 2950-2632. DOI: `10.1016/j.clwat.2024.100062`.

[39] N. Van de Giesen, R. Hut, and J. Selker, “The trans-african hydro-meteorological observatory (tahmo),” *Wiley Interdisciplinary Reviews: Water*, vol. 1, no. 4, pp. 341–348, 2014. DOI: `10.1002/wat2.1034`.

[40] Food and Agriculture Organization of the United Nations. “Crop information - land & water.” Accessed: 2025-03-11. (2025), [Online]. Available: `https://www.fao.org/land-water/databases-and-software/crop-information/en/`.

[41] A. Bokke and K. Shoro, “Impact of effective rainfall on net irrigation water requirement: The case of ethiopia,” *Water Science*, vol. 34, pp. 155–163, 2020. DOI: `10.1080/11104929.2020.1749780`.

[42] M. Chappell, J. O. Jr., S. White, and J. Lea-Cox, “Irrigation management practices,” in *Title of Book*. Publisher Name, 2013, pp. 35–36. DOI: `10.13140/2.1.4822.1767`.

[43] G. Howard, J. Bartram, A. Williams, A. Overbo, D. Fuente, and J.-A. Geere, *Domestic water quantity, service level and health*, Online, `https://iris.who.int/bitstream/handle/10665/338044/9789240015241-eng.pdf`, 2020.

[44] Noorini Izzati Mohamad Mazuki and Yeit Haan Teow and Kah Chun Ho and Abdul Wahab Mohammad, “Techno-economic analysis of single disinfection units and integrated disinfection systems for sewage effluent reclamation,” *Journal of Water Process Engineering*, vol. 36, p. 101 398, 2020, ISSN: 2214-7144. DOI: `10.1016/j.jwpe.2020.101398`.

[45] E. Dufatanye Umwali *et al.*, “Estimating the effects of climate fluctuations on precipitation and temperature in east africa,” *Atmosphere*, vol. 15, no. 12, p. 1455, 2024. DOI: `10.3390/atmos15121455`.

[46] International Renewable Energy Agency (IRENA), *Renewable Power Generation Costs in 2023*. Abu Dhabi: International Renewable Energy Agency, 2024, Accessed: 2025-06-09, ISBN: 978-92-9260-621-3.

[47] R. L. Dash, B. Mohanty, and P. K. Hota, “Energy, economic and environmental (3e) evaluation of a hybrid wind/biodiesel generator/tidal energy system using different energy storage devices for sustainable power supply to an indian

archipelago," *Renewable Energy Focus*, vol. 44, pp. 357–372, 2023, ISSN: 1755-0084. DOI: `10.1016/j.ref.2023.01.004`.

[48] A. Almasi, *Estimate pump installation costs*, Accessed: 2025-04-10, 2014. [Online]. Available: `https://www.pumpsandsystems.com/estimate-pump-installation-costs`.

[49] C. Petheram and T. Mcmahon, "Dams, dam costs and damnable cost overruns," *Journal of Hydrology X*, vol. 3, p. 100 026, Feb. 2019. DOI: `10.1016/j.hydroa.2019.100026`.

[50] Danish Energy Agency, *Technology Data - Energy Plants for Electricity and District Heating Generation.* Copenhagen: Danish Energy Agency, 2016, First published August 2016, version number: 0016, ISBN: 978-87-94447-08-9. [Online]. Available: `https://ens.dk/technologydata`.

[51] J. Elsey, "13 common factors that affect pump life," *Pumps & Systems*, 2016, Accessed: 2025-04-10. [Online]. Available: `https://www.pumpsandsystems.com/13-common-factors-affect-pump-life?utm_source`.

A

Appendix 1

This appendix contain a list of the weather variables collected, additional cost data used in the model as well as a table describing all case IDs.

A.1 List of weather variables collected

The weather variables collected originates from Trans-African Hydro-Meteorological Observatory (TAHMO) weather stations in the same region as Tabagwe. I thank the Trans-African Hydro-Meteorological Observatory (TAHMO) for the provision of meteorological data. Interested parties may contact info@tahmo.org for these data. The collected weather variables can be seen in table A.1.

Table A.1: Overview of the weather variables collected, including their notations and measurement units

Weather variable	Notation	Unit
Date	-	Day
Time	-	Hour
Atmospheric Pressure (average)	$P_{\text{atm, avg}}$	kPa
Precipitation	P	mm
Solar Radiation (average)	$G_{\text{HI, avg}}$	W/m^2
Relative Humidity (average)	RH_{avg}	- (fraction)
Air Temperature (average)	$T_{\text{air, avg}}$	°C
Wind Speed (average)	$v_{\text{wind, avg}}$	m/s

A.2 Model Input Data

Below, tables including costs considered as input parameters in the model is presented.

Table A.2: Capital investment cost per unit installed for the different technologies in the model

Technology	**CAPEX**	**Unit**	**Reference**
Solar PV	758	$/kW	[46]
Bio-diesel generator	665	$/kW	[47]
Battery	500	$/kW	[47]
Pump + Motor	400	$/kW	[48]
Dam	1.22	$/m3	[49]

Table A.3 presents, among other things, the capital recovery factor (CRF), which is the factor by which the total CAPEX is multiplied with to determine the annualized cost. The CRF is caculatead as

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{A.1}$$

where i is the interest rate and n is the lifetime in years. An interest rate of 5% has been used for all technologies in the model.

Table A.3: Operational and variable cost for the different technologies used in the model

Technology	**OPEX [% of CAPEX]**	**Variable cost [$/kWh]**	**Life time [years]**	CRF	Reference
Solar PV	5	-	30	0.0651	[50]
Bio-diesel generator	5	0.33	25	0.0710	[50]
Battery	5	-	20	0.0802	[50]
Pump + Motor	5	-	15	0.0963	[51]
Dam	5	-	50	0.0548	[49]

The cost data used for the different UV disinfection systems are shown in table A.4. The costs are based on [44] and hourly purification capacity. The cost is also doubled as the cost reference uses a purification plant not made for potable water, the doubling in cost is assumed to cover for the extra purification needed. The energy requirement for the process in the model is set to 0.023 kWh/m^3 in accordance to [34]

Table A.4: Costs for the different system used in water purification scenario

System	**Cost [$/year]**
20 l/day/person	4113
50 l/day/person	10282.5
100 l/day/person	27440
200 l/day/person	54880

A.3 Scenario and Case IDs

Table A.5: List of all scenario and case IDs with corresponding descriptions, covering base cases, water purification cases, climate change cases, and combined cases across the two different system set-ups.

Case -ID	Case Description
S0-1	Scenario 0 “Base Case” - Set-up 1
S0-2	Scenario 0 “Base Case” - Set-up 2
S1-W20c-1	Scenario 1 “Water Purification” - 20 l/person/day - constant flow - set-up 1
S1-W20c-2	Scenario 1 “Water Purification” - 20 l/person/day - constant flow - set-up 2
S1-W20d-1	Scenario 1 “Water Purification” - 20 l/person/day - daily flow - set-up 1
S1-W20d-2	Scenario 1 “Water Purification” - 20 l/person/day - daily flow - set-up 2
S1-W50c-1	Scenario 1 “Water Purification” - 50 l/person/day - constant flow - set-up 1
S1-W50c-2	Scenario 1 “Water Purification” - 50 l/person/day - constant flow - set-up 2
S1-W50d-1	Scenario 1 “Water Purification” - 50 l/person/day - daily flow - set-up 1
S1-W50d-2	Scenario 1 “Water Purification” - 50 l/person/day - daily flow - set-up 2
S1-WO-1	Scenario 1 “Water Purification” - Opportunistic case - set-up 1
S1-WO-2	Scenario 1 “Water Purification” - Opportunistic case - set-up 2
S1-W20c-ni-2	Scenario 1 “Water Purification” - 20 l/person/day - constant flow - no Irrigation - set-up 2
S1-W20d-ni-2	Scenario 1 “Water Purification” - 20 l/person/day - daily flow - no Irrigation - set-up 2
S1-W50c-ni-2	Scenario 1 “Water Purification” - 50 l/person/day - constant flow - no Irrigation - set-up 2
S1-W50d-ni-2	Scenario 1 “Water Purification” - 50 l/person/day - daily flow - no Irrigation - set-up 2
S1-W-G	Scenario 1 “Water Purification” - Grid supplied
S2-C1.6-1	Scenario 2 “Climate change” - Temperature increase 1.6 °C - set-up 1
S2-C1.6-2	Scenario 2 “Climate change” - Temperature increase 1.6 °C - set-up 2
S2-C2.0-1	Scenario 2 “Climate change” - Temperature increase 2.0 °C - set-up 1
S2-C2.0-2	Scenario 2 “Climate change” - Temperature increase 2.0 °C - set-up 2
S2-C2.4-1	Scenario 2 “Climate change” - Temperature increase 2.4 °C - set-up 1
S2-C2.4-2	Scenario 2 “Climate change” - Temperature increase 2.4 °C - set-up 2
S3-W20d-C1.6-1	Scenario 3 “Combined” - 20 l/person/day - daily flow - Temperature increase 1.6 °C - set-up 1
S3-W20d-C2.0-1	Scenario 3 “Combined” - 20 l/person/day - daily flow - Temperature increase 2.0 °C - set-up 1
S3-W20d-C2.4-1	Scenario 3 “Combined” - 20 l/person/day - daily flow - Temperature increase 2.4 °C - set-up 1
S3-W20d-C1.6-2	Scenario 3 “Combined” - 20 l/person/day - daily flow - Temperature increase 1.6 °C - set-up 2
S3-W20d-C2.0-2	Scenario 3 “Combined” - 20 l/person/day - daily flow - Temperature increase 2.0 °C - set-up 2
S3-W20d-C2.4-2	Scenario 3 “Combined” - 20 l/person/day - daily flow - Temperature increase 2.4 °C - set-up 2
S3-W50d-C1.6-1	Scenario 3 “Combined” - 50 l/person/day - daily flow - Temperature increase 1.6 °C - set-up 1
S3-W50d-C2.0-1	Scenario 3 “Combined” - 50 l/person/day - daily flow - Temperature increase 2.0 °C - set-up 1
S3-W50d-C2.4-1	Scenario 3 “Combined” - 50 l/person/day - daily flow - Temperature increase 2.4 °C - set-up 1
S3-W50d-C1.6-2	Scenario 3 “Combined” - 50 l/person/day - daily flow - Temperature increase 1.6 °C - set-up 2
S3-W50d-C2.0-2	Scenario 3 “Combined” - 50 l/person/day - daily flow - Temperature increase 2.0 °C - set-up 2
S3-W50d-C2.4-2	Scenario 3 “Combined” - 50 l/person/day - daily flow - Temperature increase 2.4 °C - set-up 2
S3-W50c-C2.4-1	Scenario 3 “Combined” - 50 l/person/day - constant flow - Temperature increase 2.4°C - set-up 1
S3-W20c-C2.4-1	Scenario 3 “Combined” - 20 l/person/day - constant flow - Temperature increase 2.4 °C - set-up 1

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se