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A Viability Analysis of Multipurpose Dam System in Rwanda

Renewable Energy for Irrigation, Electricity and Clean Water

Master's thesis in Electric Power Engineering

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Cover: Banana field in Tabagwe, Rwanda, representative of the terrain and crops in the area targeted for improved irrigation and energy access.

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Abstract

In Rwanda, where agriculture accounts for a quarter of the national GDP, improving productivity is essential due to limited opportunities to expand cultivated land. In parallel, expanding access to both electricity and clean drinking water remains a central development challenge. National strategies promote a diversified energy system, with off-grid solutions widely encouraged for rural electrification. This thesis investigates the feasibility of implementing a multipurpose dam system that supports irrigation while simultaneously enabling electricity generation and water purification through an integrated infrastructure. The analysis is based on a case study conducted in Tabagwe, Rwanda. A linear optimisation model was developed to identify the most cost-effective setup of the multipurpose dam in the focus area.

The result showed that a multipurpose dam providing irrigation, electricity, and clean water could be a viable solution for Tabagwe. These functions can be adapted to local needs and economic conditions. The most advanced configuration offered electricity access of 1 kWh capacity, available for at least 8 hours per day, sufficient to power appliances such as a refrigerator, fan, or television. It also provided 50 litres of clean water per person and was nearly 60% more expensive than the primary setup. The primary setup delivered the same amount of clean water but only provided electricity under 0.012 kWh for around 4 hours per day, enough for lighting and phone charging. UV water purification was technically feasible without system resizing, but its high capital cost made the solution financially demanding. At the same time, the system demonstrated substantial solar surplus energy, highlighting the potential to integrate alternative water purification technologies with higher energy requirements but lower costs. Further investigation into how this surplus can be better utilised or stored could enhance overall system efficiency.

Keywords: Multipurpose dam, Rwanda, Sustainability, Irrigation Management, Electricity Generation, Water Purification.

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Amelia Bergum, Alida Nilsson, Gothenburg, June 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
EDPRS2	Economic Development and Poverty Reduction Strategy 2
GDP	Gross Domestic Product
IGA	Income Generation Activities
MTF	Multi-Tier Framework
LP	Low-Pressure
OPEX	Operational Expenditure
PHS	Pumped Hydro Storage
PV	Photovoltaic
REG	Rwanda Energy Group
SDG	Sustainable Development Goals
TAHMO	Trans-African Hydro-Meteorological Observatory
USD	United States Dollar
USDA-SC	U.S. Department of Agriculture Soil Conservation Method
UV purification	Ultra-Violet Purification
WHO	World Health Organisation

Created by Kyriaki Antoniadou-Plytaria, 2021

Nomenclature

Below is the nomenclature of parameters and variables that have been used throughout this thesis.

Parameters

Δ	Slope Vapour Pressure Curve
γ	Psychometric Constant
K_c	Crop Coefficient
ρ	Density of water
g	Gravitational acceleration

Variables

ET_0	Reference Evapotransporation
ET_c	Specific Crop Evapotransporation
R_n	Net radiation at crop surface
G	Soil Heat Flux Density
T	Mean Temperature at 2 m height
u_2	Wind Speed at 2 m height
e_s	Saturation Vapour Pressure
e_a	Actual Vapour Pressure
$P_{effective}$	Effective rainfall
P_{total}	Total monthly rainfall
IN	Irrigation Need
P_{pump}	Electrical Power input to the pump
Q	Flow rate
η_{pump}	Pump efficiency

H	Net head
$P_{turbine}$	Electrical Power output from the turbine
$\eta_{turbine}$	Turbine efficiency

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Introduction

Rwanda is rapidly growing and ranks among the fastest-electrifying countries in Sub-Saharan Africa. Since 2009, the country has increased its grid connection from 6% to 54% by 2023 [1]. As of February 2025, electricity access in Rwanda reached 82% of the country's households, according to the Rwanda Energy Group (REG). Of these, 57% are connected to the national grid, while the remaining 25% rely on off-grid solutions, predominantly through solar systems [2]. This distribution aligns with the strategic direction outlined in EDPRS2, which supports the expansion of centralised grid infrastructure and decentralised off-grid systems [3]. However, electricity access remains uneven, while urban areas experiencing near total coverage, only 38% of rural areas have access. In addition to the limited coverage, the reliability of electricity is a significant challenge. Even in areas with access, frequent outages hinder consistent availability [4]. As a result, much work remains to be done to achieve the goal of universal access across the country.

In parallel with electrification efforts, national development strategies have also focused on strengthening the agricultural sector. Agriculture plays a central role in Rwanda's economy, contributing to a quarter of the GDP and providing jobs to 65% of the population [5]. In 2024, approximately 58% of the country's land area was used for agricultural purposes [6]. With limited opportunities to expand the amount of cultivated land, national development plans focus on improving yields from existing farmland. Increasing agricultural productivity is therefore a priority, given the sector's importance for livelihoods and food security [3]. The agriculture sector also faces other challenges, such as unpredictable rainfall, droughts and floods. These issues contribute to high levels of food insecurity and malnutrition, with one-third of children under five suffering from chronic malnutrition [7]. Smallholder farmers, who make up about 83% of agricultural production, are heavily dependent on rainfed agriculture. This makes them particularly vulnerable to the effects of climate change, which further disrupts rainfall patterns and agricultural productivity.

Another challenge Rwanda faces is access to clean drinking water. According to UNICEF, just 57% of the population has access to clean drinking water within a 30-minute distance from their homes [8].

This thesis investigates the potential of a multipurpose dam to improve irrigation, electricity access, and clean water supply in Rwanda. By examining the country's energy, agricultural, and water sectors, the study considers how such a system could contribute to national development goals and enhance rural livelihoods. The analysis is based on a case study in Tabagwe, a rural village in the Eastern Province.

1.1 Literature Review

To support Rwanda's development goals in energy and food production, several innovative dam projects are either under construction or already in operation. One project is the Muvumba Multipurpose Dam, which is currently being built. The dam is designed to store 55 million m^3 of water, enabling irrigation of 9 000 hectares of farmland and providing water for livestock. In addition, the system aims to supply 50 000 m^3 of clean water for domestic use and generate approximately 7 000 MWh of electricity annually for the national grid, using two turbines with a combined capacity of 1 MW [9]. The Muvumba project aligns with Rwanda's National Strategy for Transformation (NST-1) and Vision 2050, both of which identify agricultural productivity and water management as key foundation of socio-economic growth [10].

Chandra et al. [11] evaluated a community-based irrigation scheme in Rwanda, where smallholder farmers shared access to irrigation infrastructure. The study found notable gaps between modeled crop water needs and actual irrigation practices. Despite this underirrigation, crop yields improved, suggesting that even limited access to irrigation can enhance productivity. The authors also emphasized the importance of proper irrigation planning to further improve system performance and farmer outcomes.

Uwitije et al. [12] emphasise the importance of accurately estimating irrigation suitability and energy demand when designing microgrid systems for off-grid agricultural settings. The study shows that electrifying irrigation can boost productivity, but also results in substantial seasonal variation in energy demand. This creates opportunities for utilising surplus energy during periods of lower agricultural load, potentially supporting other productive uses within the community.

Nkuriyingoma et al. [13] evaluated a grid-connected solar PV system integrated with a Battery Energy Storage System (BESS) to supply electricity to a rural community of 100 households in Rwanda. The system was designed to maximise self-sufficiency and support both household electricity needs and a water pumping system for agriculture. Simulation results showed an annual energy consumption of 82.34 MWh and a peak load of 30.4 kW.

Hassan et al. [14] investigated a solar-powered irrigation system for groundwater extraction in Egypt and found that it could achieve high performance, with a performance ratio ranging from 49% to 72% depending on the season. The study also noted that incorporating water storage tanks in place of batteries reduced both installation and maintenance costs, thereby improving the system's overall cost-effectiveness.

Furthermore, Favi et al. [15] evaluated the efficiency of a photovoltaic-powered irrigation system in rural Niger. Their findings showed that while oversizing the PV array relative to the pump's requirements led to only a modest increase in overall

efficiency, and it significantly reduced the pump's efficiency. This demonstrated the value of proper component matching in PV-powered systems.

The Thwake Multipurpose Dam, currently under construction in Kenya, is designed to provide irrigation, hydropower, and domestic water to benefit approximately 1.3 million people [16]. While multipurpose dam projects are often initiated to enhance livelihoods and support long-term development, a study by Owour et al. [17] on the Thwake project in Makueni County highlights the potential for negative social impacts. The research found that the construction process disrupted local livelihoods, weakened social networks, and adversely affected the local economy. These findings underscore the importance of thorough planning to minimise displacement and reduce disruptions to everyday life. The Thwake project shares contextual similarities with Tabagwe, the case village examined in this thesis, particularly in the community's reliance on subsistence farming and lack of electrification.

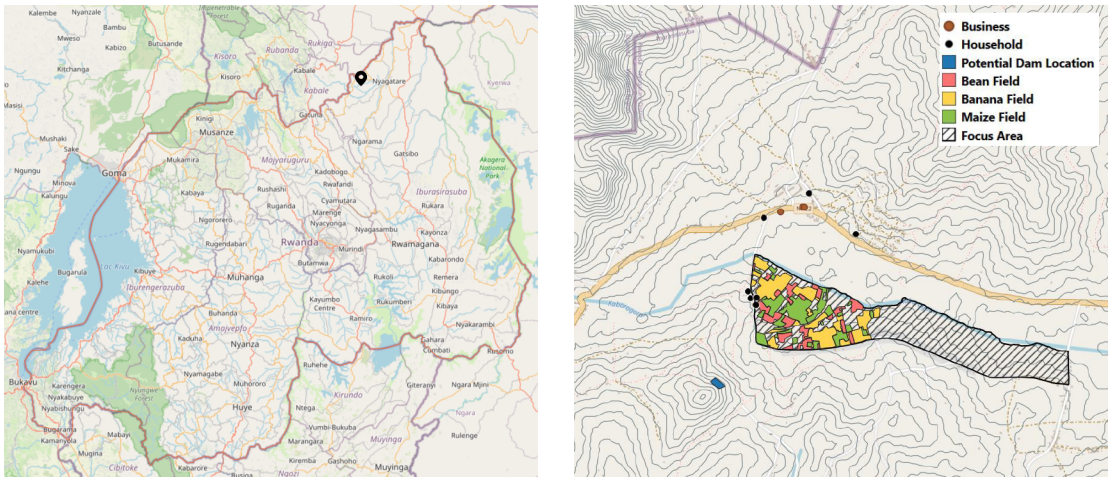
Riva et al. [18] conclude that rural electrification is shaped by complex and context-specific dynamics. The study challenges the common assumption of linear, one-way benefits from increased electricity access and highlights the difficulty of appropriately sizing rural energy systems, particularly in off-grid contexts. Instead, it finds that electricity use is closely linked to various aspects of socio-economic development, such as income generation, household economy, health, education, and social networks. To ensure realistic system planning and long-term impact, the authors stress the need to account for these interdependencies alongside supportive measures like capacity-building and awareness initiatives.

Rwanda has introduced several initiatives to improve agricultural productivity and expand energy access. Notable examples include the Nyabarongo II [19] and Akanyaru multipurpose projects [20], which aim to address multiple development goals simultaneously. Existing literature primarily focuses on hydrological factors such as inflow patterns, catchment characteristics, and the benefits of irrigation for agriculture. However, research on the practical implementation of integrated, multifunctional systems remains limited. In particular, few studies evaluate the viability of combining irrigation with additional services. To address this gap, this thesis examines the feasibility of a solar-powered multipurpose dam system that uses pumped hydro storage to supply irrigation, electricity, and clean water.

1.2 Background

A field study was conducted in Tabagwe, a small village in the Eastern Province of Rwanda, to gain insights into local infrastructure and community conditions. The village has approximately 1 565 inhabitants.

Two figures are shown below. The first indicates the location of Tabagwe within Rwanda. The second provides a detailed view of the focus area, including the village layout, the Uganda border, and the Kaborogota River. The map legend highlights site features. A medium voltage grid runs along the main road, with low voltage connections supplying houses near the road and in the village center. Black and brown dots mark the locations where community engagement activities were carried out, representing households and businesses. The blue area shows the proposed dam site. Crop types are marked in red for beans, yellow for bananas, and green for maize. The hatched boundary outlines the focus area included in the study.



(a) Location of Tabagwe in Rwanda **(b)** Close-up of Tabagwe focus area

Figure 1.1: Maps showing the location and site features of the focus area in Tabagwe

Engagement with community members showed that electricity supply is unreliable and capacity is limited. Households with access typically use two to three lamps in the evening and one outdoor lamp overnight. Mobile phones are generally charged every few days. This usage corresponds to an estimated daily electricity consumption of about 75 Wh, which aligns with enhanced Tier 1 access under the Multi Tier Framework [21].

The focus area lies south of the Kaborogota River and covers approximately 96 hectares, of which around 88 hectares are farmland. The area is home to about 750 people across roughly 150 households. A field survey was conducted on a smaller portion of the farmland, approximately 50 hectares, to observe the proportions of banana, maize, and bean cultivation. These observed proportions were then scaled up to estimate crop distribution across the entire 88 hectares of agricultural land.

The proportions are summarized in Table 1.1. Most households practice subsistence agriculture, primarily growing beans, maize, and bananas. Surplus harvests are occasionally sold at local markets.

This part of Tabagwe is not connected to the national electrical grid. Most households rely on small solar panels, which were subsidised by the government between 2021 and 2024 [22]. These panels provide basic electricity for lighting and phone charging. However, during the rainy seasons, solar generation is often insufficient, resulting in extended periods without electricity.

Rwanda's climate is characterised by alternating rainy and dry seasons, which define three agricultural periods known as Seasons A, B and C. Season A spans from September to February [23], beginning with a rainy period and typically transitioning into a short dry season from December to February [24]. Season B occurs from March to June [25], a period that typically brings the long rainy season [24]. Season C corresponds to the long dry period between July and August. Community members highlighted a significant lack of water during this time, which negatively impacts agricultural productivity. It was observed that farming activities mainly take place during Seasons A and B, which coincide with the two rainy periods. Season C is only cultivated by households that have access to irrigation systems. Since many farmers rely on rainfed agriculture, farming activities during Season C are generally only feasible if an irrigation system is available [26]. In contrast, Seasons A and B are widely used for cultivation across the country [27].

Understanding the timing and structure of these seasons is essential for planning crop cycles and water management strategies. In the focus area of this study, the primary crops cultivated were maize, banana and beans. Their respective growing periods and the proportion of cultivated land they occupy are presented in Table 1.1.

Table 1.1: Crop areas and active growing seasons for the irrigated region.

Crop	**Area**	**Growing Season**
Maize	30%	September to February (Season A)
Banana	51%	Year round
Beans	19%	March to June (Season B)

While rainfed agriculture has traditionally provided sufficient crop yields in most years, occasional inconsistencies in rainfall patterns have led to reduced harvests. Studies show that climate variability is one of the most significant factors affecting annual agricultural production [29]. In addition, changing climate conditions are expected to alter seasonal rainfall dynamics, particularly in drier regions such as the Eastern Province where future rainfalls may become more intense but occur over shorter periods [29]. Given these trends, irrigation systems are increasingly seen as an important adaptation strategy. By supplementing rainfall during the growing season and enabling cultivation during dry periods, irrigation can improve both the

reliability and productivity of agricultural yields [30], [31]. However, access to irrigation remains limited for many smallholder farmers, who constitute the majority of Rwanda's agricultural producers. This points to the need for appropriate, scalable and sustainable water supply solutions that align with local conditions and cropping patterns.

Furthermore, during the discussions with the community, access to clean drinking water was reported as a major challenge. Most households collect their water from a piped source. However, the water is untreated and not safe for drinking without purification. Community members expressed a desire for improved access to clean water.

The field study and engagement with the community were used to confirm and complement information from the National Development Plans and district statistics. The insights gathered provided a broader understanding of local conditions and guided the system design to better respond to the community's needs.

1.3 Aim

This project aims to assess how a multipurpose dam system can provide irrigation, electricity, and/or clean water to Tabagwe, a village in rural Rwanda. The objective is to find the most cost-effective solution to meet the needs of the community by utilising pumped hydro storage powered by solar energy.

1.4 Scope

The research question for this project is:

Is a multipurpose dam a viable solution for providing cost-effective irrigation and/or domestic electricity, and/or clean water to Tabagwe village through the integration of pumped hydro storage powered by solar energy?

This question is addressed through the following sub-objectives:

1. Investigate the cost and capacity requirements for a single-purpose dam based irrigation system to support local agriculture in Tabagwe.
2. Assess how interannual rainfall and weather variability affect the robustness of the base irrigation model.
3. Evaluate the technical and economic viability of integrating household electrification into the single-purpose dam, creating a dual-purpose dam.
4. Evaluate the technical and economic viability of combining water purification with the irrigation system into the single-purpose dam, creating a dual-purpose dam.
5. Analyze the integration of irrigation, electricity generation, and water purification into a multipurpose dam from a cost-effective perspective.

These sub-objectives are evaluated based on the focus area shown in Figure 1.1, taking into account the main crops cultivated, the number of inhabitants, and current electricity usage patterns.

1.5 Limitations

Due to time constraints and data limitations, several assumptions and simplifications were made in the system design and modelling process. The linear programming model excludes installation and implementation costs. While the optimisation focuses on minimising capital and operational expenses, real-world deployment would also involve substantial additional costs for transport, construction, site preparation, and labour. These omitted factors could significantly affect the total system cost and the relative feasibility of different configurations. Due to limited site-specific data, such as estimates for transport and construction, these costs were not included in the analysis. As a result, only investment and operational expenditures were considered in the optimisation.

Weather data was collected from THAMO, an independent provider with stations near the research area. However, no stations were located directly within the study area, instead being approximately 23 km away. This introduces uncertainty, as local weather can vary over short distances, and the data may not fully reflect actual conditions. Furthermore, the dataset was limited to four years of historical data, which may not capture long-term climatic variability. As a result, the model may produce over- or under-dimensioned system configurations that do not account for extreme weather events beyond the observed period.

Crop selection was based on the Seasonal Agricultural Survey [27] and engagement with the local community. The model included maize, beans, and banana, three of the most commonly cultivated crops. It was assumed that maize is grown from September to February (Season A), beans from March to June (Season B), and bananas are produced year-round. While this reflects a common cropping pattern, other crops are also grown, and rotations may vary. Consequently, the model simplifies local cropping dynamics and may over- or underestimate irrigation needs in some areas.

To account for uncertainties in sowing dates, maximum crop coefficient (K_c) values were applied throughout the growing season for each crop. Although this approach may slightly overestimate irrigation during some phases, it reduces the risk of under-dimensioning the system in cases where planting occurs earlier or later than expected. This choice supports flexibility in accommodating variation in growing patterns. The specific $K_{c,max}$ values used in this study are provided in Appendix A.1.

The model also assumed unlimited access to water from the Kaborogota River, which flows from Uganda. In reality, the river experiences seasonal variation with lower flow during the dry season. Due to unavailable flow data, this variability was not included. As a result, the model assumes water is always available throughout

the year, which may not reflect actual conditions, especially during prolonged dry periods. This simplification, along with the model's perfect foresight of weather conditions, reduces the complexity of managing reservoir storage and release. In practice, such uncertainties can affect the sizing of pumps, storage, and overall system performance. These factors were not taken into account in this study due to data limitations but should be kept in mind when interpreting the results. Therefore, the dam's charging and discharging operations are only considered to occur when electricity is available or required.

2

Theory

2.1 Crop Water Requirement

The crop water requirement is the total amount of water a crop needs to grow optimally throughout its development without experiencing water stress. Crop water requirements vary depending on the type of crop, local climate, and weather conditions. The evapotranspiration is the total amount of water that leaves the soil and plants and goes into the air. To estimate these requirements, the FAO Penman-Monteith equation is used to calculate reference evapotranspiration, which forms the basis for determining the water demand of different crops. Effective rainfall is also considered, as it represents the portion of rainfall that contributes to meeting crop water needs through natural precipitation. This section presents the theoretical concepts used to estimate crop water demand and calculate irrigation requirements.

2.1.1 FAO Penman-Monteith Equation

The FAO Penman-Monteith equation is a standard method for determining reference evapotranspiration based on local meteorological data. This value represents the water demand of a hypothetical reference crop under standardized conditions, providing a baseline for estimating irrigation requirements in a given climatic context [34]. The corresponding equation is given by:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2.1}$$

Where

- ET_0 is the reference evapotranspiration [mm/day]
- R_n net radiation at the crop surface [MJ/(m$^2 \cdot$ day)]
- G soil heat flux density [MJ/(m$^2 \cdot$ day)]
- T mean daily air temperature at 2 m height [°C]
- u_2 wind speed at 2 meters height [m/s]
- e_s saturation vapour pressure [kPa]
- e_a actual vapour pressure [kPa]
- Δ slope vapour pressure curve [kPa/°C]
- γ psychometric constant [kPa/°C]

2.1.2 Water Requirements for Crops

To move from the reference evapotranspiration value to the specific crop evapotranspiration, the reference value ET_0, is multiplied by the crop coefficient K_C. The equation is expressed as:

$$ET_C = ET_0 \cdot K_C \tag{2.2}$$

Where ET_0 is determined by eq. (2.1) and K_C is a crop coefficient specific to different crops. This coefficient is influenced by parameters such as crop height, ground cover, rooting depth, and other crop characteristics. The result is a crop-specific evapotranspiration value adjusted for the climatic conditions of the location [35].

2.1.3 Effective rainfall

Effective rainfall represents the portion of total rainfall that is available to the crop and contributes to meeting the specific crop evapotranspiration demand (ET_c). It is an important factor in estimating the irrigation requirement, as it reflects the water naturally supplied to the crops. The irrigation deficit is calculated as the difference between the crop water requirement and the effective rainfall [36].

Several approaches exist for estimating effective rainfall, and one is the USDA Soil Conservation (USDA-SC) method, which provides the minimum net irrigation water requirement [37]. The USDA-SC method is defined by Equation 2.3, depending on the total monthly rainfall [38]:

$$P_{\text{effective}} = \begin{cases} P_{\text{total}} \times \dfrac{125 - 0.2 \cdot P_{\text{total}}}{125}, & \text{for } P_{\text{total}} < 225 \text{ mm} \\ 125 + 0.1 \times P_{\text{total}}, & \text{for } P_{\text{total}} \geq 225 \text{ mm} \end{cases} \tag{2.3}$$

where P_{total} is the total monthly rainfall [mm].

The method first groupes the daily rainfall data into 10-day intervals, commonly referred to as decades. For each decade, the total rainfall is calculated and used as input to Equation 2.3. The resulting effective rainfall for each 10-day period is then proportionally distributed across the individual days, based on their share of the total rainfall within that period.

2.1.4 Irrigation Requirement

The water requirement for a crop can be met by rainfall, irrigation, or a combination of both. Irrigation requirements depend on both the crop water demand and the effective rainfall [39]. The irrigation need (IN) for a crop, taking effective rainfall into account, is calculated as follows:

$$IN = ET_C - P_{\text{effective}} \tag{2.4}$$

where IN is the irrigation need, ET_C is the crop evapotranspiration (crop water requirement), and $P_{\text{effective}}$ is the effective rainfall. These variables are defined in previous subsections.

2.2 Pumped Hydro Power Plant

Pumped Hydro Power Plants serves both large-scale energy systems and decentralised applications in remote or rural areas where grid access is limited. This section outlines the technical principles and integration of pumped hydro with solar PV systems, focusing on both the pumping and generation processes.

2.2.1 Pumped Hydro for Energy Storage

The core of pumped hydro storage (PHS) technology lies in the conversion between electrical and gravitational potential energy [40]. When surplus electricity is available, typically during off-peak hours or from intermittent sources as solar, water is pumped from a lower reservoir to an upper reservoir [41]. This stored energy can later be released by allowing the water to flow back down through a turbine, generating electricity on demand.

PHS is a widely adopted and mature technology, with an efficiency ranging between 70 and 85 %. One of its advantages is the negligible self-discharge, meaning that energy remains effectively stored without significant losses over time [40].

2.2.2 Pump

In pumped hydro systems, the pump is responsible for lifting water to a higher elevation, converting electrical energy into hydraulic potential energy. A common choice is the fixed-speed centrifugal pump, which operates at a constant rotational speed and delivers flow based on the available power and system pressure.

The hydraulic power required by the pump is calculated using Equation 2.5 [42]:

$$P_{\text{pump}} = \frac{\rho \cdot g \cdot Q \cdot H}{\eta_{\text{pump}}} \tag{2.5}$$

where

- P_{pump} is the electrical power input to the pump [W]
- ρ is the density of water [kg/m^3]
- g is the gravitational acceleration [m/s^2]
- Q is the flow rate [m^3/s]
- H is the net head [m]
- η_{pump} is the efficiency of the pump [-]

2.2.3 Turbine

The pumped water is stored in the upper reservoir until energy is needed. When released, the water flows through a turbine, converting hydraulic energy into mechanical energy, which is then converted to electricity by a generator. The power output of the turbine is given by Equation 2.6 [43]:

$$P_{\text{turbine}} = \rho \cdot g \cdot Q \cdot H \cdot \eta_{\text{turbine}} \tag{2.6}$$

where

- P_{turbine} is the electrical power output from the turbine [W]
- ρ is the water density [kg/m^3]
- g is the gravitational acceleration [m/s^2]
- Q is the flow rate [m^3/s]
- H is the net head [m]
- η_{turbine} is the turbine efficiency [-]

2.2.4 Solar PV and Pumped Hydro Integration

In rural regions with limited or unreliable access to the electrical grid, micro-grids are increasingly being adopted to meet local energy needs. These micro-grids are often powered by solar photovoltaic (PV) systems, which generate electricity only during daylight hours and are subject to daily and seasonal variability.

To address the intermittent nature of solar generation, PHS can be integrated as a complementary storage solution. During daytime hours, surplus solar electricity is used to pump water to the upper reservoir. When solar generation drops or electricity demand increases, the stored water is released through a turbine to provide reliable power. This synergy enables a more stable and resilient energy supply in off-grid settings [41].

2.3 Multi-Tier Framework

The Multi-Tier Framework (MTF) provides a more nuanced way to measure electricity access than binary connection-based metrics [21]. Rather than simply stating whether a household is connected to the grid, the MTF evaluates how well that access meets the household's needs. It considers a range of attributes, including power capacity, duration, reliability, and the inclusion of off-grid solutions, to assess the extent to which electricity access is functional and sufficient.

The MTF is structured into five tiers, where each higher tier reflects greater access in terms of power availability and service duration. These attributes are summarised in Table 2.1, which outlines the minimum power capacity and duration required for each tier level.

Table 2.1: Multi-Tier Metrics for Electricity Access.

Metric	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Power	3 W	50 W	200 W	800 W	2 kW
Capacity	12 Wh	200 Wh	1.0 kWh	3.4 kWh	8.2 kWh
Duration	4 h/day	4 h/day	8 h/day	16 h/day	23 h/day

2.4 Water Purification and Treatment Techniques

There are several water purification techniques that are widely used today, each with its own advantages depending on context and resource availability. In rural, off-grid areas where access to electricity and chemical supplies may be limited, UV disinfection offers an effective alternative. It is a non-chemical method that inactivates microorganisms using ultraviolet light, making it appropriate for decentralized water treatment solutions. UV disinfection is also cost-effective and allows for easy adjustment of the UV dose to meet water safety requirements [44]. This section explains the principles behind UV disinfection and presents cost and performance parameters.

2.4.1 UV Disinfection for Water Purification

UV disinfection inactivates microorganisms by damaging their DNA with ultraviolet light, which prevents them from reproducing and causing infection. A common source used in water treatment systems is the low-pressure (LP) mercury lamp [45]. It emits ultraviolet light at a wavelength of 253.7 nm, which lies within the optimal germicidal range of 200–280 nm [46]. This makes LP lamps both energy efficient and fitting for decentralized applications.

Essential technical parameters of the UV disinfection unit are presented in table 2.2.

Table 2.2: UV disinfection cost effectiveness parameters

Parameter	LP	Reference
Biocidal Efficiency [%]	35-38	[46]
Lamp life [hours]	8000-10 000	[46]
Wavelength [nm]	253.7	[46]
Energy Intensity [kWh/m^3]	0.017	[47]

3
Methods

This chapter outlines the modeling process used to assess the feasibility and performance of a multipurpose dam that provides irrigation, electricity, and/or clean water. The methodology describes the systematic model design, presents the modelling choices made during model construction, and outlines the assumptions made in cases where data were insufficient. The model was developed to simulate the performance of a dam system under various operational scenarios. The starting point was a Base Model representing a single-purpose irrigation dam. Scenario 0 was introduced to evaluate the robustness of the Base Model by examining the effects of annual weather fluctuations on system performance. From the Base Model, additional functions were introduced in separate scenarios. Scenario 1 combined irrigation with household electrification, resulting in a dual-purpose dam, while Scenario 2 combined irrigation with water purification, forming another dual-purpose configuration. Finally, Scenario 3 integrated all three functions, irrigation, electrification, and water purification, into a multipurpose dam. Based on these scenarios, several cases were simulated. The methodology explored operational synergies and evaluated the system by comparing total costs across different scenarios and their respective capacities. Each scenario is presented by outlining the investment and the benefits provided.

Figure 3.1 shows a flowchart of the Base Model and the scenarios. The blue labels at the top illustrate the functional options, which are inserted into the purple squares and provide an overview of the single-, dual-, and multipurpose dam configurations. The green labels show the different cases of the dam system, which are further described in the tables 3.1, 3.2 and 3.3.

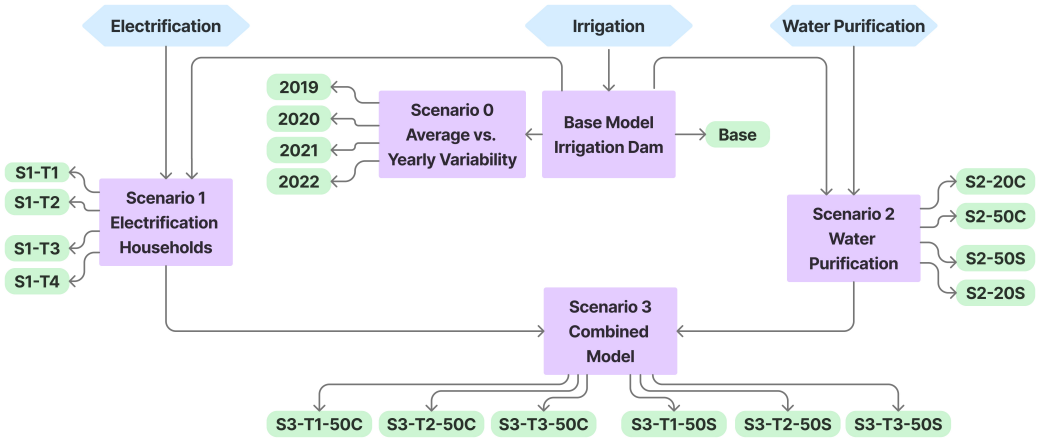


Figure 3.1: Flowchart of Model Construction

3.1 Model

A linear optimisation model was developed to design a cost-effective system and evaluate the potential of a dam system capable of providing irrigation, electricity, and clean water in different setups, creating a single-, dual- or multipurpose dam. The model was optimised with hourly time resolution. Simulating the system under realistic operating conditions, reflective of real-world functionality, enabled the exploration of different design choices and their consequences. This approach offered an efficient way, in terms of time and cost, to evaluate whether the system was suitable for implementation. Details on the applied constraints and parameters can be found in the Appendix.

Before initiating the modelling process, the daily irrigation schedule was determined. The weather data collected from the local weather station contained occasional missing values. To address this, linear interpolation was used to estimate the missing data points based on adjacent hourly values. The interpolated values were inserted into the weather dataset to obtain a more complete and continuous time series. The net crop water requirement was calculated using the FAO Penman-Monteith Equation (Eq. 2.1), based on weather parameters from a nearby weather station, and with the crop-specific coefficients (Eq. 2.2). The total water demand was then adjusted according to a fixed cultivation schedule for the three main crops, each assigned a proportional share of the cultivated area. The effective rainfall was calculated with the USDA-SC method, shown in Equation 2.3. This method provides the minimum net irrigation water requirement and is therefore appropriate for regions with limited water availability [37]. By subtracting effective rainfall from the total crop water requirement, the final daily irrigation need was derived. This daily irrigation demand was then distributed evenly across a seven hour irrigation window, with four hours in the morning (06:00–10:00) and three hours in the evening (18:00–21:00).

The total crop water requirement for each crop was presented in the irrigation output, showing the contribution from effective rainfall and the remaining irrigation demand to be met by the system. Results were provided for both annual fluctuations and average irrigation needs, in order to highlight interannual variation and trends. These irrigation demand profiles served as input to the optimisation model, forming the basis for dimensioning the reservoir and pump capacities under varying climatic and cropping conditions.

To reflect typical climatic conditions, the model was run separately for each year from 2019 to 2022 using hourly weather data from College de Rushaki, a nearby TAHMO station [48]. For each year, the model calculated the required system capacities based on weather and irrigation demand inputs. The results from all four years were then averaged to produce a single representative system configuration, which is referred to as the Base Case. This averaging approach was applied consistently across all scenarios, unless otherwise specified.

3.2 Base Model: Irrigation Dam

The Base Model constructed the design of a single-purpose reservoir system capable of meeting the daily irrigation requirements for crops in the focus area. The model was dimensioned with the aim of achieving a cost-effective configuration that ensures sufficient water availability throughout the year. Optimisation was carried out using linear programming, allowing the model to efficiently allocate resources under defined constraints. It integrated local topographic inputs, including head height at the proposed dam site, visualised in Figure 1.1b.

The model used the preprocessed daily irrigation demand profile together with hourly solar irradiation data. For each year, the system was optimised to determine suitable capacities for the solar PV array, pump, and reservoir. The system was dimensioned to meet irrigation needs year-round. The outputs from these annual simulations were then averaged to generate a representative system configuration, which served as the Base Case for subsequent scenario development.

A schematic of the system is shown in Figure 3.2, illustrating the reservoir with an assumed uniform depth of 10 m, pump, solar panels, and irrigation sprinkler. This Base Case configuration served as the basis for further analysis, where additional functionalities and system improvements could be explored.

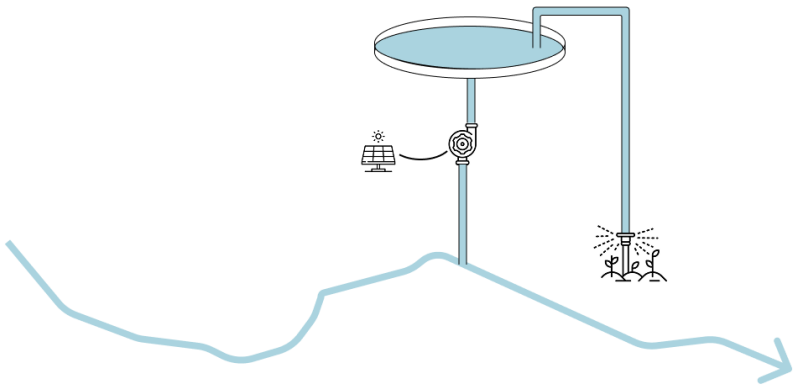


Figure 3.2: Layout of the Base Model: Irrigation Dam

The model output included optimal system capacities for the solar PV array, pump, and reservoir, as well as hourly operation schedules and water availability throughout the year. These results were used to assess system performance under varying weather conditions and served as the foundation for extending the model to include electricity generation and water purification in the additional scenarios.

3.3 Scenario 0: Average vs. Yearly Variability

To evaluate the effect of interannual variability, the model was run separately using weather data from each year between 2019 and 2022. For each simulation, the system was optimised to meet the irrigation demand specific to that year by adjusting the reservoir size, pump power, and solar PV capacity. This allowed for a direct comparison of system performance and design requirements across varying climatic conditions.

Subsequently, Scenario 0 was constructed by applying the Base Case configuration, based on the average component sizes from the four individual optimisations, to each year. This enabled an assessment of how a fixed design performs under different annual conditions, with attention to energy use, surplus generation, and the system's capacity to meet irrigation demand.

To further evaluate the robustness of the Base Case, a sensitivity analysis was carried out to examine how consistently the fixed capacities could satisfy demand across all years. The analysis focused on the proportion of the net crop water requirement that could be met under each year's conditions.

This scenario was conducted prior to incorporating electricity generation and water purification components, in order to ensure that the irrigation system design was sufficiently resilient when considered independently.

3.4 Scenario 1: Household Electrification

Scenario 1 extended the Base Model to incorporate household electricity access, creating a dual-purpose dam system that supports both irrigation and electrification. In this configuration, a turbine was added at the reservoir outlet, allowing the system to operate as a form of solar-powered pumped hydro storage. Water lifted using solar energy for irrigation could also be released through the turbine to generate electricity, enabling time-shifted renewable energy delivery.

In contrast to the irrigation demand in the Base Model, which followed a fixed daily schedule but varied seasonally, the electricity demand was modelled as uniform in both timing and quantity across all days of the year. A schematic of the system is shown in Figure 3.3, illustrating the Base Model components alongside the added electricity generation function.

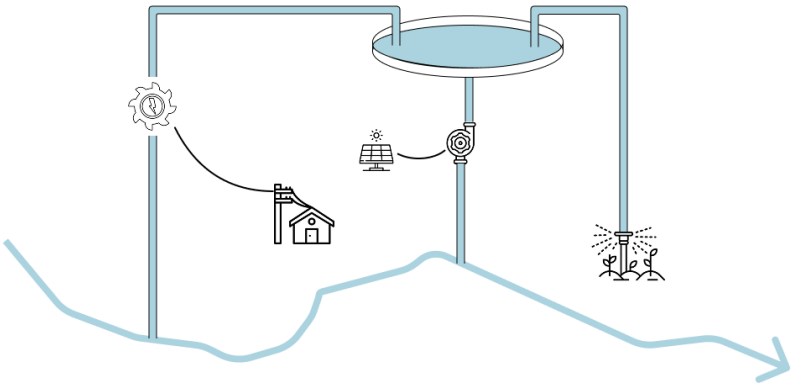


Figure 3.3: Layout of the Irrigation System with Household Electrification

To evaluate the impact of different electrification levels on system performance, four cases were simulated based on the Multi-Tier Framework for household electricity access. Each case corresponds to a different daily electricity demand, ranging from Tier 1 to Tier 4. Tier 5 was excluded from this study due to its significantly higher power requirements, which fall outside the practical scale of systems suitable for rural deployment in this project. The simulated cases are labeled S1-T1 to S1-T4, as shown in Table 3.1. Higher tiers were associated with increased electricity generation requirements, which were modeled by adjusting the water flow through the turbine accordingly.

Table 3.1: Scenario 1: Case configurations by electrification level.

Case	Description
S1-T1	Electrification level: Tier 1
S1-T2	Electrification level: Tier 2
S1-T3	Electrification level: Tier 3
S1-T4	Electrification level: Tier 4

To reflect realistic household electricity usage patterns for each tier level, time-based supply restrictions were applied in the model. In Cases S1-T1 and S1-T2, electricity supply was limited to two fixed intervals per day: 07:00–08:00 in the morning and 18:00–21:00 in the evening. Case S1-T3, representing a higher access level according to the Multi-Tier Framework shown in Table 2.1, extended the supply window to 06:00–09:00 in the morning and 18:00–23:00 in the evening. In Case S1-T4, which corresponded to the highest tier of electricity access considered, the supply was available for 16 hours during the day 06:00-10:00 and during 11:00-23:00 in the evening. For all cases, electricity generation was scaled to meet the combined demand of 150 households in the focus area.

The optimisation model determined the cost-effective configuration of solar PV capacity, pump power, and reservoir size for each electrification tier. The objective function minimised total annualised system costs, covering both capital and operational expenses, subject to constraints on energy and water balance, storage limits, and operational feasibility.

Outputs such as electricity generation, pump energy use, and surplus solar energy were analysed hourly. Comparisons were made across tiers and against the Base Case to evaluate the impact of household electrification on total cost, component sizing, and overall system behaviour.

3.5 Scenario 2: Water Purification

Scenario 2 integrated the Base Model developed for irrigation with an additional water purification system, forming an alternative dual-purpose configuration. In this scenario, the energy demand of the purification system was analysed alongside the existing energy requirements of the Base Model. Unlike the irrigation load, which varies seasonally, the electricity demand for purification was implemented as a fixed daily load to represent a consistent clean water target. The configuration consisted of two subsystems, a dam system and a UV-based water purification system. A schematic of the setup is shown in Figure 3.4, illustrating the Base Model components together with the added purification system.

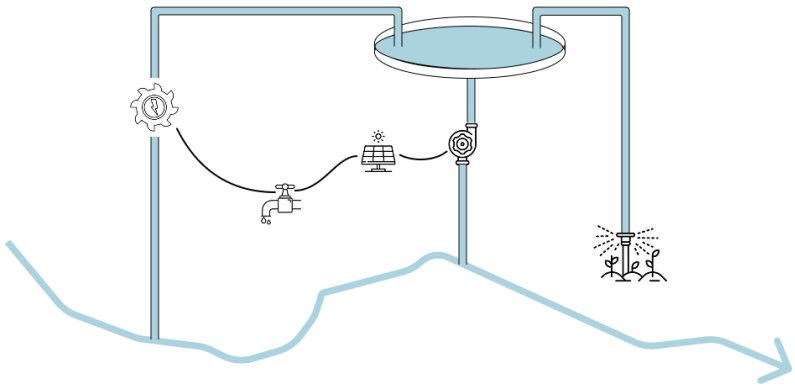


Figure 3.4: Layout of the Irrigation System with Water Purification

The system was dimensioned according to WHO recommendations for basic and intermediate daily clean water availability per person. The water purification system was scaled to meet the combined demand of 1565 people in the focus area, as detailed in Subsection **??**. Four cases were explored, including variations in both the amount of water to be supplied and the timing of delivery. The analysis evaluated whether it was more cost-effective to expand the capacity of the base model, including a turbine for electricity generation to enable continuous water purification, or to retain the original system size and operate the purification unit only when excess energy was available, as in Cases S2-20S and S2-50S. The different cases considered in Scenario 2 are presented in Table 3.2.

Table 3.2: Scenario 2 case definitions by purification volume and operation mode

Case	Description
S2-20C	20L Constant Water Purification
S2-50C	50L Constant Water Purification
S2-20S	20L Surplus Water Purification
S2-50S	50L Surplus Water Purification

For the constant purification cases, S2-20C and S2-50C, the system was designed to supply fixed daily clean water volumes of 20 L and 50 L per person, respectively. Electricity for purification was provided at a constant rate using a turbine powered solely by solar-charged hydro storage, mirroring the dam system configuration in Scenario 1. The turbine operated continuously throughout the day to meet the steady energy demand of the UV purification system, ensuring reliable clean water production regardless of solar variability.

In the surplus energy cases, S2-20S and S2-50S, the water purification system was modelled to operate only when solar generation exceeded the pump energy requirement. The layout of this dam system was identical to the Base Model. Since purification relied entirely on solar surplus energy, it did not follow a fixed delivery

schedule. Therefore the operation was run at higher intensities over shorter periods. On days without sufficient surplus no purification can take place.

3.5.1 Population Estimation for Water Purification System

The water purification system was dimensioned based on the estimated number of inhabitants living within a 1 km radius of the system. As the exact population within the covered area of 3.12 km^2 was unknown, the population density of the Tabagwe Sector was used to approximate it. This density was calculated using the total area and population of the sector and then applied to the modelled area. This approach resulted in an estimated population of approximately 1 565 inhabitants within the covered area, which was used to dimension the water purification system and determine the corresponding clean water requirement.

3.5.2 Establishment of Economical Parameters

The water purification system was dimensioned based on technical and economic data from a case study conducted in Malaysia, where a UV-based system was evaluated for treating wastewater into non-potable water [44]. As no site specific water quality data for the water in Tabagwe was available, it was assumed that a system approximately twice as large would be required to meet domestic standards. This assumption was also applied to the cost, resulting in an estimated CAPEX equal to twice that of the reference system. To estimate the CAPEX cost of the purification system designed for Tabagwe, a linear relationship between system size and cost was assumed.

The UV lamps used in the purification system were assumed to have a lifespan of approximately 9 000 hours, corresponding to one year of continuous operation. In the opportunistic operation scenario, the system was assumed to pump with full capacity when there was excess energy during sunshine hours, and the lamps were therefore expected to require replacement after a period of 5.25 years. The UV lamps were assumed to be the most cost-intensive component of the system, and other operational expenditures were therefore considered negligible. As a result, no recurring OPEX costs were included, and it was assumed that a new system investment would occur at the end of the UV lamps' operational lifetime.

3.6 Scenario 3: Combined Model

The combined model was developed by integrating selected cases from Scenario 1 and Scenario 2 that showed promising individual performance. These were evaluated together to assess the system's ability to simultaneously deliver irrigation, electricity, and clean water through a multipurpose configuration. The model was designed to address the overall aim of the study, which was to evaluate a cost-effective dam system capable of meeting multiple community needs. A schematic of the setup is presented in Figure 3.5, illustrating how components from Scenarios 1 and 2 were integrated into a single multipurpose system.

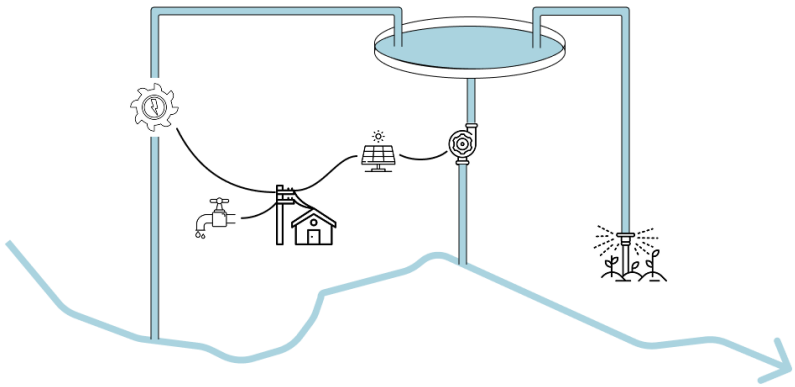


Figure 3.5: Layout of the Irrigation System with combined Scenario 1 and 2

As in the previous scenarios, the model was optimised to minimise the total system cost while satisfying the combined demands of irrigation, household electricity, and clean water provision. The simulation output included the optimal capacities of the solar PV system, pump, turbine, reservoir, and water purification.

The multipurpose dam scenario was constructed by combining Scenarios 1 and 2, using selected case configurations. For Scenario 1, the configurations selected for inclusion in the combined approach were S1-T1, S1-T2, and S1-T3. Case S1-T4 was not included, as the associated system capacities exceeded the scale considered appropriate for the study context. From Scenario 2, only the larger water purification configurations, S2-50C and S2-50S, were simulated. This approach provided greater dam system flexibility, allowing for the implementation of either a large or a smaller purification unit, depending on future needs and economic capacity. The simulated cases are listed in Table 3.3.

Table 3.3: Scenario 3: Combined configurations by tier and purification strategy.

Case	Description
S3-T1-50C	Tier 1 & 50L Constant Water Purification
S3-T2-50C	Tier 2 & 50L Constant Water Purification
S3-T3-50C	Tier 3 & 50L Constant Water Purification
S3-T1-50S	Tier 1 & 50L Surplus Water Purification
S3-T2-50S	Tier 2 & 50L Surplus Water Purification
S3-T3-50S	Tier 3 & 50L Surplus Water Purification

The results were analysed to assess how the combined configuration affected system performance, particularly in terms of overall energy utilisation, cost efficiency, and component sizing. Comparisons were made with Scenarios 1 and 2 to evaluate trade-offs and synergies in the combined approach, and to determine whether it aligned more closely with either scenario or showed a different overall outcome.

4
Results

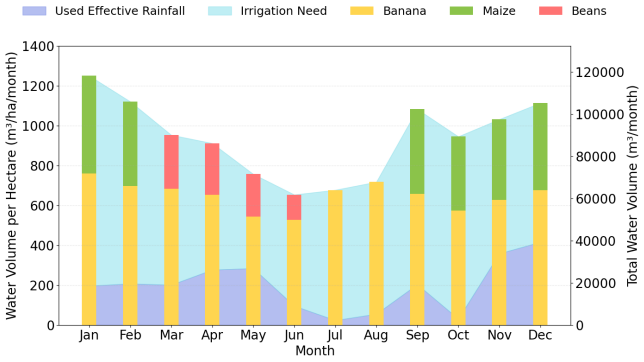
This chapter presents the outcomes of the simulation models, beginning with a single-purpose irrigation dam and expanding to dual- and multipurpose configurations. The analysis starts with crop water requirements, which define the irrigation demand inputs to the base model. Scenario 0 evaluates the base irrigation system under different years of climate data. Scenario 1 adds household electrification, while Scenario 2 includes water purification. Scenario 3 combines all three services into a multipurpose system.

Each scenario was assessed in terms of system sizing, energy use, reliability, and cost, highlighting how the added functions influenced the performance and infrastructure. The results revealed trade-offs and synergies that arose during the integration of functions.

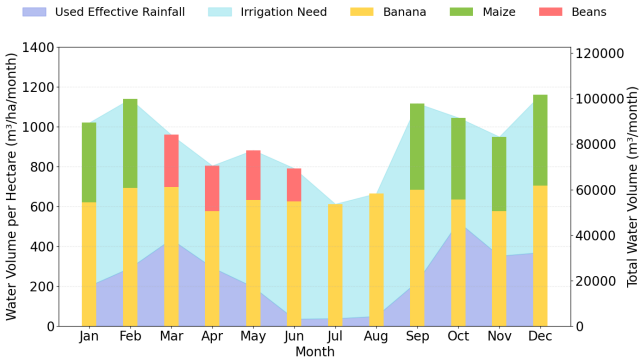
4.1 Crop Water Requirements and Irrigation Needs

Crop water requirements and irrigation needs were assessed for the focus area based on the types of crops grown, their seasonal growth stages, and local weather conditions. Table 1.1 summarises the main crops, their growing periods, and respective proportions. The analysis draws on TAHMO weather data from the College de Rushaki station for the years 2019 to 2022 [48].

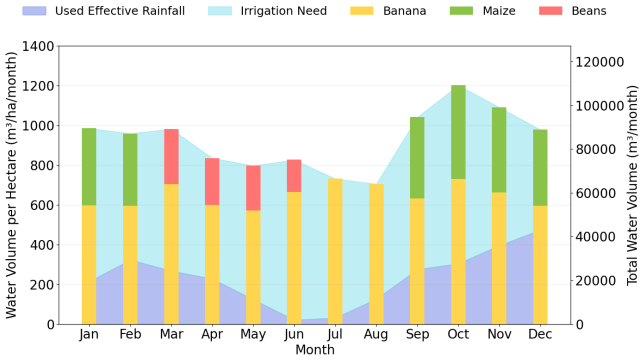
Each figure displays the crop water needs for banana, maize, and beans throughout the year, represented in yellow, green, and pink, respectively. The effective rainfall used is shown in purple and is determined based on the crop schedule and daily evapotranspiration ET_c. The irrigation requirement is the difference between the daily crop water need and the effective rainfall, and it is presented in blue. This irrigation demand reflects the amount of water needed to fully meet the crop water requirements and achieve maximum yield.



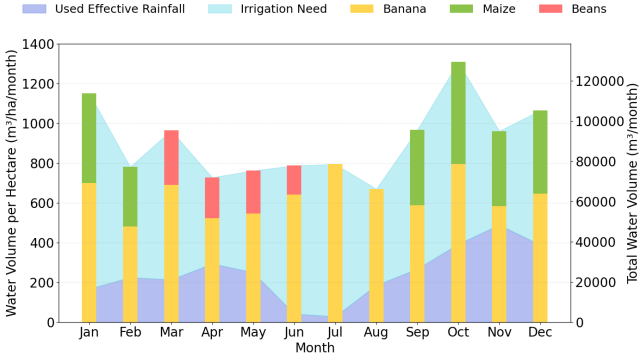
(a) Irrigation Requirement for 2019



(b) Irrigation Requirement for 2020



(c) Irrigation Requirement for 2021



(d) Irrigation Requirement for 2022

Figure 4.1: Monthly Irrigation per Hectare and Total Volume [48]

It can be observed that the irrigation requirements vary between years. When comparing the month of January across different years, the crop water requirement for 2019 exceeds 1200 m^3/ha/month, whereas in 2021 it is just below 1000 m^3/ha/month, with 2020 and 2022 falling in between. The lowest points of crop water requirement each year occur during the months May to August, with a difference of around 200 m^3/ha/month between the years, typically ranging between 600 and 800 m^3/ha/month.

The peaks in irrigation demand occur in September and October for 2020, 2021, and 2022, and in January for 2019, all reaching around 1200 m^3/ha/month. The effective rainfall used in the model shows varying patterns across years. During wet seasons, peak effective rainfall reaches approximately 50 m^3/ha/month. In dry periods, it drops to around 50 m^3/ha/month, corresponding to a 90 % reduction compared to wet periods.

Overall, while the yearly trends differ, the highest peak values are very similar across years, and the minimum values vary slightly but not significantly. In the following analysis, an average of the four years is presented, smoothing out random variations and creating a more stable trend. Although this approach provides a clearer overall pattern, it does not capture the year-to-year noise seen in the individual annual data. Figure 4.2 shows both the water volume per hectare per month and the total water volume per month.

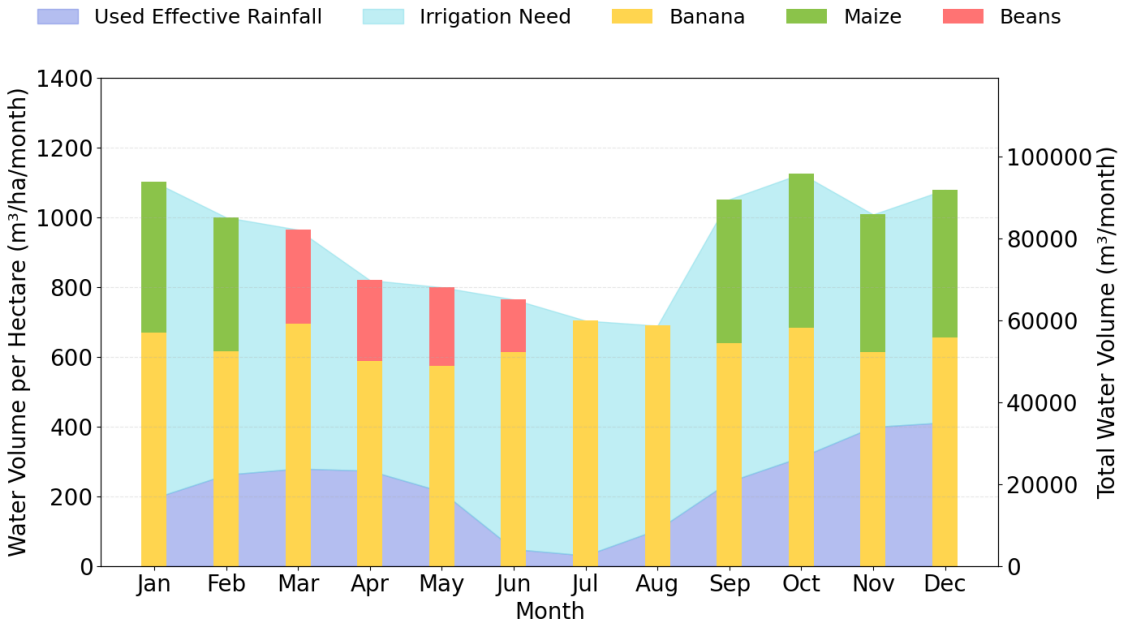


Figure 4.2: Average Irrigation per Hectare and per Total Volume [48]

The total water volume represented the full crop water balance, including both the specific crop water requirements and the contribution from effective rainfall. From this, the irrigation need was derived as the remaining volume that had to be supplied artificially when rainfall was insufficient. The total water volume is used

as the basis for designing the irrigation system. On average, the monthly peak reaches approximately 95 000 m^3/month. However, when the crop water need is at its highest, the used effective rainfall contributes at least 18 500 m^3/month, thereby reducing the required irrigation volume. Across the year, the monthly irrigation volume per hectare varies between 680 m^3/ha/month and 1150 m^3/ha/month.

4.2 Base Model: Irrigation Dam

Building on the identified irrigation needs, the base model simulates a system configuration designed to meet water demand under local site conditions. The resulting reservoir volume, solar capacity, and pump capacity define the initial parameters, referred to as the 'Base Case'.

The following tables present the average system specifications and associated operational metrics for the base case. These are discussed in detail in the paragraphs that follow.

Table 4.1: Optimal System Capacities and Annualized Costs for Base Case

Component	Capacity	Annual CAPEX	Annual OPEX	Total Annual Cost
Reservoir	9 119 m^3	$610	$556	$1 166
Pump	265 kW	$10 197	$5 294	$15 491
Solar	395 kW	$19 496	$14 974	$34 470
Total		**$30 303**	**$20 825**	**$51 127**

Table 4.2: Dam Annual Operation Metrics for Base Case

Scenario	Energy utilisation	Surplus Energy	Pumping Energy	Total Water Pumped
Base Case	70.89 %	154 MWh	372 MWh	735 000 m^3

The Base Case system includes a solar capacity about 1.5 times larger than the pump capacity. The system delivers over 730 000 m^3 of water annually. The energy surplus corresponds to 29% of the total solar energy generated and reflects a system-level constraint in energy utilisation. Although the solar capacity is sufficient to meet irrigation demand across the year, it regularly exceeds the system's ability to pump water due to limitations in pump capacity and reservoir storage. As a result, a significant portion of the available solar energy remains unused, highlighting a gap between generation and utilisation under the current configuration

The total annual system cost is estimated at $51 127, with $30 303 allocated to capital expenditure and $20 825 to operational expenditure. As shown in Table 4.1, the reservoir contributes only $1 166 annually. This represents less than 3% of the

total system cost. While low in cost, its physical footprint requires careful site selection to minimize environmental and social impacts. As an example, assuming a uniform depth of 10 meters, its surface area would be approximately 912m^2.

The pump and solar components account for the majority of total system costs. The pump has an annual cost of $15 491, including $10 197 in capital expenditure and $5 294 in operational costs. Approximately one-third of the pump cost is attributed to operation. The solar installation has a total annual cost of $34 470, made up of $19 496 in capital costs and $14 974 in operational costs. The solar cost is more than twice the total annual cost of the pump. In contrast to the pump, the capital and operational costs of the solar installation are more evenly distributed. The solar system accounts for approximately 67% of the total annual cost, making it the primary economic driver of the system.

4.3 Scenario 0: Average vs. Yearly Variability

To examine the effect of interannual variability, the model was run separately using weather data from each year between 2019 and 2022. Scenario 0 evaluates annual performance by applying this Base Case to each individual year. The results illustrate how year-to-year climate variability influences energy utilisation, surplus generation, and the system's ability to meet irrigation demand.

The tables below present the system sizing, total annual cost and operational performance results for each individual year from 2019 to 2022. Table 4.3 shows the required reservoir volume, pump capacity and solar capacity for each year. Table 4.4 presents the corresponding annual operational metrics using these year specific capacities. In both tables, the average row corresponds to the base case, which was defined by averaging the results from all four years.

Table 4.3: System component capacities and total annual cost by year using year-specific weather data.

Year	Reservoir	Pump	Solar	Total Cost
2019	8 955 m^3	290 kW	403 kW	$53 282
2020	7 242 m^3	285 kW	416 kW	$53 895
2021	14 545 m^3	221 kW	359 kW	$46 100
2022	5 734 m^3	263 kW	402 kW	$51 232
Average*	9 119 m^3	265 kW	395 kW	**$51 127**

** Average corresponds to the Base Case.*

Table 4.4: Annual operation metrics by year using year-specific system capacities.

Year	Energy utilisation	Surplus Energy	Pumping Energy	Total Water Pumped
2019	74.31 %	137 MWh	396 MWh	782 000 m^3
2020	66.26 %	185 MWh	363 MWh	717 000 m^3
2021	77.51 %	108 MWh	373 MWh	736 000 m^3
2022	65.48 %	188 MWh	357 MWh	704 000 m^3
Average*	70.89 %	154 MWh	372 MWh	735 000 m^3

** Average corresponds to the Base Case.*

The capacities of the system varied between the four years modeled, as shown in Table 4.3. Reservoir volumes ranged by a factor of more than 2.5, from the smallest in 2022 to the largest in 2021. Pump capacities differed by nearly 70 kW, representing a difference of over 40 %, with the lowest value in 2021 and the highest in 2019. Solar capacities were more stable, with a spread of 57 kW between the smallest and largest years. Across all years, solar capacity remained approximately 1.5 times larger than pump capacity. The smallest system configuration occurred in 2021, with the lowest pump and solar capacities and the largest reservoir. In contrast, the largest solar PV system appeared in 2020, alongside a relatively high pump capacity and the smallest reservoir. Although the maximum pump and solar capacities occurred in different years, the top two years for each component were close in size. The difference was only 5 kW for the pump and 13 kW for the solar system. The ratio between solar and pump capacities remained consistent, suggesting that sizing was influenced by year-specific climate conditions.

The total annual system cost also varied between the four years, with a difference of approximately 15% from the lowest to the highest value. Costs in 2019, 2020 and 2022 remained within a relatively narrow range, while 2021 was distinctly lower, reducing the overall average. The lowest cost in 2021 coincided with the smallest pump and solar capacities and the largest reservoir. The highest cost in 2020 corresponded to the largest solar capacity and a relatively high pump size. Additionally, years with similar solar capacities, such as 2019 and 2022, still showed a difference of over $2 000 in total cost due to differences in pump capacity and reservoir size. These results indicate that pump and solar capacities have a stronger influence on total cost than reservoir volume.

Operational performance across the years showed notable variation, as summarised in Table 4.4. Energy utilisation differed by 12 percentage points, with the highest value in 2021 and the lowest in 2022. Compared to 2021, energy utilisation in 2022 decreased by approximately 16 %, while the difference between 2019 and 2020 was around 8 %.

Surplus energy varied significantly across the years, ranging from 108 MWh in 2021 to 188 MWh in 2022, an increase of approximately 74 %. The results highlight strong

year-to-year variability in the balance between solar generation and system demand. The two years with the highest surplus energy also had the lowest energy utilisation rates, indicating that a larger share of generated energy was not used. This points to a mismatch between system capacity and operational demand under certain climate conditions.

Pumping energy showed relatively minor variation across the study period. The difference between the highest annual value in 2019 and the lowest in 2022 was approximately 39 MWh, representing a spread of about 10 %. The figures across all four years remained within a narrow range, indicating a relatively stable level of operational energy demand.

The difference in total annual water pumped between years reached 78 000 m^3 between the highest and the lowest year, representing a variation of approximately 10 %. The years 2020 and 2021 showed relatively minor differences, with a variation of less than 3 %. Overall, 2020 and 2022 demonstrated the most consistent performance across all operational metrics, with only small differences between them in energy utilisation, surplus energy, pumping energy, and total water pumped.

Although system capacities varied significantly between years, these differences did not always align with trends in operational performance. For example, 2021 had the highest reservoir volume but the lowest pump and solar capacities, while also achieving the highest energy utilisation and the lowest energy surplus. In contrast, 2022 had the smallest reservoir and relatively high solar capacity but resulted in the lowest energy utilisation and highest surplus. Similarly, 2019 combined the highest solar and pump capacities with a midrange reservoir size and achieved the highest pumping energy and total water volume but not the highest utilisation. These mismatches show that differences in capacity sizing alone do not consistently explain variations in performance metrics across years. Instead, the data suggest that system outcomes result from a combination of sizing and year specific climate conditions.

Another way to illustrate the differences in system behavior across the years is through daily storage dynamics. While the previous tables summarize annual capacities and performance metrics, Figure 4.3 shows the full-year daily variation in stored water volume for each year. Year 2019 is shown in dark blue, 2020 in light blue, 2021 in pink, and 2022 in yellow. The black dotted line represents the average reservoir volume used in the Base Case system.

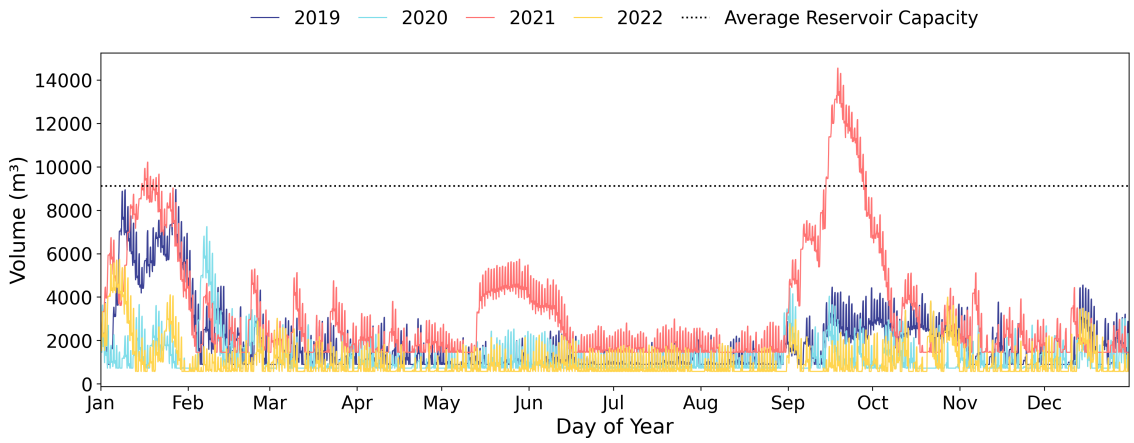


Figure 4.3: Daily Stored Water Volume [48]

Figure 4.3 highlights clear seasonal trends in reservoir storage across the years. January and February consistently show the highest storage levels for all four years with volumes often above 7000 m^3. From March through early May, storage levels gradually decline. Year 2021 shows a notable increase in storage from mid May to mid June reaching around 6000 m^3, a pattern not observed in other years. Between mid June and early September all years show low storage levels typically between 1000 and 3000 m^3. From mid September storage rises again, especially in 2019 and 2020 reaching up to 4000 m^3, while 2022 remains consistently low throughout the year. These patterns suggest a combination of recurring seasonal behaviour and year-specific fluctuations. It is therefore relevant to distinguish between typical trends and unusual peaks to understand how storage is utilised across different years.

Year 2021 stands out clearly from the other years with a sharp rise in storage in September that peaks above 14 000 m^3 in early October. This peak is more than 250 % higher than any other year during the same period marking 2021 as an extreme case. If 2021 had not been included in the analysis the resulting reservoir size would have been significantly smaller. This highlights the sensitivity of system design to the choice of input years used in the analysis. For example, the outcome would have been very different if the design had been based only on 2022. This emphasizes the uncertainty of generalising system performance from these four years and suggests that future conditions may require system configurations that differ from those tested here.

The following analysis evaluates how each individual year performs when operated using the Base Case system capacities. This was done to assess whether the system can consistently meet daily irrigation demand under yearly varying weather conditions. Table 4.5 summarises the annual irrigation performance, reporting the total irrigation deficit, the number of deficit days, and the percentage of days on which full irrigation demand was met. Table 4.6 presents selected days with irrigation shortfalls, including the size of the deficit, the change in storage over the day, and the percentage of the daily irrigation need that was met.

Table 4.5: Annual irrigation performance under Base Case capacities.

Year	Total Irrigation Deficit	Irrigation Deficit	Irrigation Met
2019	5 016 m^3	8 days	97.81 %
2020	1 382 m^3	4 days	98.90 %
2021	0 m^3	0 days	100.00 %
2022	1 325 m^3	2 days	99.45 %

Table 4.6: Daily irrigation shortfalls with storage change and percentage of irrigation demand met.

Date	Irrigation Deficit	Storage Change	Irrigation Met
2019-01-02	253 m^3	-661 m^3	95.02 %
2019-01-03	641 m^3	134 m^3	82.27 %
2019-02-01	420 m^3	-824 m^3	92.21 %
2019-02-02	630 m^3	-322 m^3	84.94 %
2019-02-03	1 093 m^3	101 m^3	76.50 %
2019-02-04	1 289 m^3	295 m^3	74.37 %
2019-02-05	539 m^3	4 m^3	84.76 %
2019-11-05	151 m^3	-681 m^3	96.89 %
2020-01-01	96 m^3	-432 m^3	97.85 %
2020-01-02	713 m^3	49 m^3	84.73 %
2020-01-03	400 m^3	-80 m^3	90.22 %
2020-02-14	173 m^3	-251 m^3	94.51 %
2022-01-12	527 m^3	-363 m^3	89.29 %
2022-01-13	799 m^3	213 m^3	82.09 %

Across the four modeled years the system met full irrigation demand on all days in 2021. In 2022 this occurred on 99.45 % of days, in 2020 on 98.90 % of days, and in 2019 on 97.81 % of days. This corresponds to zero deficit days in 2021, two in 2022, four in 2020, and eight in 2019. Table 4.6 presents the days with irrigation deficits, showing the shortfall magnitude, end-of-day storage change, and percentage of irrigation need met.

While any unmet demand is recorded as a deficit day, not all shortfalls are equally severe. Several cases fall within a narrow margin, with over 95% of the irrigation demand still met. For example, on January 1 in 2020, 97.85% of the required irrigation was delivered, and on November 5 in 2019, 96.89% was met. In contrast, some days had more substantial shortfalls, such as February 3 in 2019, when only 77% of the demand was fulfilled.

On several days, a deficit occurred even though end-of-day storage increased. This is due to the fixed irrigation schedule, which allows pumping only during defined morning and evening windows. As a result, available energy or water later in the

day could not be used to reduce the shortfall. For instance, on January 3 in 2019 and January 2 in 2020, storage increased by the end of the day despite recorded deficits. This pattern is observed in at least five of the fourteen deficit days.

4.4 Scenario 1: Household Electrification

This scenario examines the impact of introducing household electricity access alongside the existing irrigation system. Four electricity access levels were considered: Tier 1, Tier 2, Tier 3, and Tier 4, each representing increasing daily household demand and longer delivery windows. These tiers correspond to the cases S1-T1, S1-T2, S1-T3, and S1-T4 in the results. Differences in load structure between irrigation and electricity influenced system operation across tiers. While irrigation volumes fluctuated daily, electricity demand remained constant in both timing and energy. This contrast affected energy allocation, component utilisation, and overall system sizing as household electrification was introduced.

The first comparison focuses on system component sizing across the tiers. Table 4.7 shows the required reservoir volume, pump capacity, solar capacity, and turbine size for each configuration.

Table 4.7: Optimal average system capacities across tiers for 150 households.

Case	Reservoir	Pump	Solar	Turbine
Base	9 119 m^3	265 kW	395 kW	0.00 kW
S1-T1	9 089 m^3	267 kW	400 kW	0.45 kW
S1-T2	8 736 m^3	314 kW	469 kW	7.50 kW
S1-T3	10 137 m^3	441 kW	743 kW	30 kW
S1-T4	7 879 m^3	641 kW	13 959 kW	120 kW

Table 4.7 shows how system capacities evolve across tiers with increasing electricity demand. In S1-T1, the reservoir volume decreases by 0.3% relative to the Base Case, while pump and solar capacities increase by less than 1%. A small turbine of 0.45 kW is introduced, marking the initial addition of hydropower capacity to the system.

S1-T2 introduces more noticeable changes. Pump and solar capacities both increase by about 19% relative to Base Case, while the reservoir shrinks by 4.2%. The turbine capacity increases to 7.50 kW, offering a moderate expansion in hydropower generation.

In S1-T3, the reservoir expands by 11.2%, with pump and solar capacities reaching 441 kW and 743 kW, representing increases of 66.4% and 88.1% over the Base Case. The turbine scales up to 30 kW, reflecting further infrastructure growth.

S1-T4 results in the most extreme configuration. The reservoir remains nearly unchanged, decreasing by just 0.4%. The pump capacity increases to 641 kW, a 142%

rise compared to the Base Case, reflecting the substantially higher water delivery rates required. This increase is driven by the power capacity being set at 800 W per household, which is double that of S1-T3, combined with a daily operation duration of 16 hours, also twice that of S1-T3. Since the system relies on solar power available primarily during approximately 5 hours of sunlight per day, the pumping and energy supply must be concentrated within this limited period. Consequently, the solar capacity expands dramatically to 13 959 kW, an increase of over 3435%, to meet these intensified energy demands during sunshine hours. The turbine capacity also grows to 120 kW, indicating a large-scale hydropower installation capable of supporting substantial system loads.

Overall, the first three tiers, S1-T1 through S1-T3, require progressively larger but proportionate scaling of system components. S1-T4 shows a sharp departure, with solar capacity increasing by more than a factor of 30 and pump capacity more than doubling. While the reservoir remains relatively stable across all tiers, the substantial increase in energy infrastructure, particularly solar, highlights the intensity of resources required to meet higher levels of electricity demand. The steady increase in turbine capacity reflects the growing reliance on hydropower support as demand levels rise.

The second comparison focuses on operational performance across the electrification tiers. Table 4.8 presents annual system utilisation, surplus energy generation, total electricity produced by the turbine, and the minimum required energy associated with each tier.

Table 4.8: Annual system operation metrics across tiers for 150 households

Case	System Utilisation	Surplus Energy	Rated Turbine Output	Min Tier Required
Base	70.89 %	154 MWh	0.0 MWh	0.0 MWh
S1-T1	71.27 %	154 MWh	3.9 MWh	0.7 MWh
S1-T2	77.24 %	142 MWh	66 MWh	11 MWh
S1-T3	82.25 %	176 MWh	263 MWh	88 MWh
S1-T4	12.99 %	16476 MWh	1051 MWh	701 MWh

System utilisation quantifies the proportion of solar energy consumed by the pump. Additionally, it accounts for increased energy use when stored water is released to generate hydropower that contributes to meeting electricity demand. System utilisation is how much of the solar energy is used by the system. The system utilisation increases steadily from the Base Case through S1-T3, rising from 70.89 % to 82.25 %. This progression reflects the system's growing ability to use available energy as electricity demand increases. In S1-T4, however, utilisation drops sharply to 12.99 %, indicating that the system is vastly oversized for the corresponding demand. This efficiency drop marks a critical threshold, beyond which the existing configuration becomes unsuitable for higher tiers.

Surplus energy remains unchanged between the Base Case and S1-T1, confirming

that adding S1-T1 electricity demand has negligible impact on the overall energy balance. S1-T2 records the lowest surplus across all tiers at 142 MWh, while also achieving a high utilisation of 77.24 %. This suggests a closer match between generation and demand compared to the other cases. S1-T3 reaches the highest utilisation at 82.25 %, but its larger system size results in a greater absolute surplus of 176 MWh. In contrast, S1-T4 generates 16 476 MWh in surplus, which is more than 100 times that of the Base Case.

Rated turbine output also scales sharply across the scenarios. Compared to S1-T1, the output in S1-T2 is over 15 times greater, about 67 times greater in S1-T3, and nearly 270 times greater in S1-T4. Minimum turbine energy required grows in parallel, from 0.70 MWh to 701 MWh, reflecting the longer operating hours and increased electricity demand associated with the higher tiers.

Overall, S1-T1 demonstrates that electricity access at its lowest level can be integrated with no significant changes to system sizing aside from the addition of a small turbine, making it a low-impact and easily achievable upgrade. S1-T2 stands out as the configuration with the lowest surplus energy and strong system utilisation, reflecting an efficient and balanced design. S1-T3 achieves the highest energy utilisation, indicating the most effective performance under the current system configuration. S1-T4, however, marks a breaking point. Despite massive infrastructure scaling, system utilisation drops below 13 % and surplus energy increases dramatically. These results suggest that the Base Case design is no longer viable for the demands of S1-T4 and that a fundamentally different system architecture would be needed to operate efficiently at this level of electricity access.

Figure 4.4 illustrates the average annual energy flows for each case. Solar generation is shown in yellow, pump energy demand in dark blue, energy surplus in light blue, rated turbine electricity in green, and the minimum tier requirement in pink.

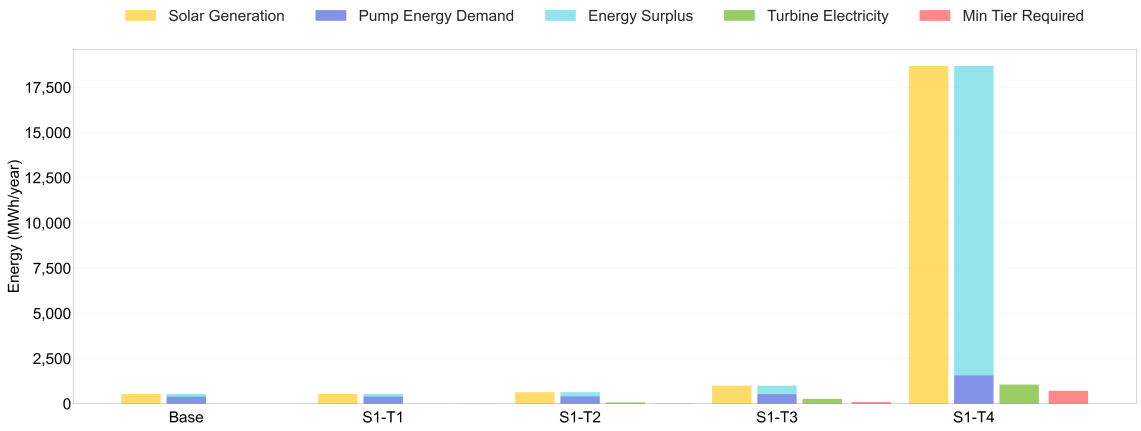


Figure 4.4: Energy across Tiers [48]

Figure 4.4 illustrates the energy flows across all tiers. Solar generation remains relatively similar from the Base Case through S1-T3, with only moderate increases needed to support additional electricity demand. In contrast, S1-T4 shows a dras-

tic jump in generation, confirming that this configuration requires a fundamentally different system scale. The earlier tiers maintain a reasonable balance between generation, usage, and surplus, while S1-T4 produces far more energy than needed, highlighting its inefficiency and lack of feasibility within the current system design.

The final comparison focuses on total system costs and their breakdown across components. Table 4.9 presents the annualized cost of the reservoir, pump, solar and turbine for each case.

Table 4.9: Annualized cost breakdown for system components across tiers for 150 households.

Case	Reservoir	Pump	Solar	Turbine	Total
Base	\$1 166	\$15 491	\$34 470	\$0	\$51 127
S1-T1	\$1 162	\$15 620	\$34 891	\$20	\$51 694
S1-T2	\$1 117	\$18 394	\$40 925	\$337	\$60 773
S1-T3	\$1 296	\$25 803	\$64 827	\$1 346	\$93 272
S1-T4	\$1 007	\$37 516	\$1 217 859	\$5 386	\$1 261 768

Upgrading the system from the base case to S1-T1 results in an increase of \$567, which corresponds to approximately 1.1% higher annual cost. This change reflects small increases in pump and solar costs, and the addition of a turbine contributing \$20 annually. The reservoir cost remains nearly unchanged. Despite the minor cost difference, this configuration enables the system to supply up to 3.9MWh of electricity per year to 150 households, demonstrating that basic electrification can be added with almost no impact on total cost.

The transition to S1-T2 leads to a cost difference of \$9 646 compared to the base case, representing an 18.9% increase. This increase reflects a larger turbine contributing \$337, and expanded solar and pump capacities adding \$6 455 and \$2 903 respectively. The reservoir cost decreases slightly. This increase alone adds nearly one fifth of the total system cost when compared to the Base Case. In return, the system delivers up to 65.7 MWh of electricity per year, about 1 567% more than S1-T1.

In the case of S1-T3, the annual cost rises by \$42 145 relative to the Base Case, an increase of approximately 82.5%. The solar and pump components see major jumps, with solar costing nearly twice as much and the pump more than 1.6 times higher than in the Base Case. The turbine cost increases to \$1 346. This configuration supports up to 262 800 kWh of annual electricity, four times more than S1-T2 and nearly seventy times more than S1-T1.

S1-T4 presents a dramatic escalation in cost, rising by \$1 210 641 above the base case. This corresponds to an increase of about 2 367%, making it nearly 25 times more expensive than the base system. The configuration is dominated by solar infrastructure at \$1 217 859, with the pump and turbine contributing \$37 516 and

$5 386 respectively. Although turbine costs remain modest, the scale of solar and pumping required to meet electricity demand at this level drives the total cost to its highest point.

Across all tiers, increases in total system cost were primarily associated with scaling the solar and pump components, which remained the dominant cost contributors. Electricity demand introduced an additional energy load that required more water to be lifted using solar power. In these configurations, water was stored at elevation and later released through the turbine, enabling time-shifted renewable energy delivery. Although turbine components added minimal cost, their operation depended entirely on water already lifted by the solar-powered pumping system.

4.5 Scenario 2: Water Purification

This scenario builds on the Base Case irrigation system by adding water purification as a fixed daily electricity load. The added demand corresponds to supplying clean water for 1 565 people. Two access levels were evaluated based on daily needs of 20 liters and 50 liters per person. To meet this demand, two system configurations were simulated. One supplies electricity at a constant rate using a turbine through solar-powered hydro storage. The other relies on surplus solar energy, using the existing dam infrastructure to power purification when available, without affecting the energy supply allocated for pumping.

4.5.1 Powering Water Purification by Turbine

In this approach, water purification is powered using a turbine operating as part of a solar-powered hydro storage system. The configuration is identical to that used in Scenario 1 where water is lifted using solar energy, stored at elevation and released in a controlled manner to generate electricity. The turbine runs each hour to supply a constant electricity output that meets the fixed purification load. The process is assumed to operate evenly across the day. Table 4.10 presents the optimized system capacities required to meet this load including reservoir volume, pump and solar capacities and the added turbine size.

Table 4.10: Dam system component capacities for water purification scenarios

Case	Reservoir	Pump	Solar	Turbine
Base	9 119 m^3	265 kW	395 kW	0.00 kW
S2-20C	9 117 m^3	265 kW	395 kW	0.02 kW
S2-50C	9 114 m^3	265 kW	396 kW	0.06 kW

Table 4.10 presents the dam system component capacities across the water purification scenarios. The reservoir size decreases slightly from the Base Case to S2-50C, indicating a more dynamic use of stored water as purification demand increases. Pump capacity remains unchanged across all cases, while solar capacity increases by only 1 kW between the Base Case and S2-50C, suggesting that the additional

energy required for purification is minimal. A turbine is introduced in the purification scenarios, but remains small in all cases, reflecting the low and steady energy demand of the UV treatment process.

In the following table, the annual system utilisation, turbine energy output, and cost breakdown are summarised for the turbine powered water purification cases. Table 4.11 includes the dam system cost, the purification cost based on clean water delivery, and the resulting total annual cost for each case. These values show how small purification loads influence overall system behaviour and total cost as access levels increase.

Table 4.11: Annual operation and cost summary for dam upgrades and water purification.

Case	System utilisation	Turbine Energy	Dam Annual Cost	Purification Annual Cost	Total Annual Cost
Base	70.89 %	0 kWh	$51 127	$0	$51 127
S2-20C	70.92 %	194 kWh	$51 154	$8 582	$59 736
S2-50C	70.95 %	486 kWh	$51 298	$21 456	$72 754

Table 4.11 shows how the system responds to the added electricity demand for water purification when powered by a turbine. System utilisation increases by 0.03 % between each case, indicating that the added purification load has minimal impact on overall system behavior. Turbine energy generation in S2-50C is approximately 2.5 times higher than in S2-20C, but still remains negligible compared to the system's annual surplus energy.

The dam's annual cost increases only slightly. From the base case to S2-20C, the increase is $27, and from there to S2-50C, an additional $144, resulting in a total rise of just 0.3 %. This confirms that enabling the dam to generate electricity for purification can be achieved without significant upgrades to infrastructure or additional operating costs.

The purification cost is calculated separately and reflects the energy required to operate the treatment system. In S2-50C, it is 150% higher than in S2-20C, consistent with the increased clean water demand. Compared to the base case, the total annual cost increases by 17% in S2-20C and by 42% in S2-50C. This sharp rise adds significant pressure to the overall system cost. The results indicate that electricity generation for purification can be integrated with minimal modifications to the dam infrastructure, but the main cost burden lies in the UV-purification technology itself.

4.5.2 Supply Water Purification by Surplus Energy

This approach explores whether the dam system can support water purification using only the surplus solar energy that remains after meeting pumping demand. Unlike the turbine-powered method, which assumes a constant purification load, this configuration uses excess solar energy whenever it becomes available. As a

result, purification occurs at variable times and flow rates depending on the daily energy surplus. While the load is not distributed evenly across the full day, it is concentrated during sunshine hours due to the nature of solar generation and must operate at higher intensities over shorter periods. On days with no available surplus, purification cannot occur. Table 4.12 shows the number of days per year when sufficient surplus energy was available to meet the required purification levels.

Table 4.12: Annual clean water supply from surplus energy.

Year	Energy Used S2-20S	Energy Used S2-50S	Clean Water	Clean Water Coverage
2019	155 kWh	388 kWh	292 days	80.00 %
2020	169 kWh	423 kWh	318 days	86.89 %
2021	176 kWh	440 kWh	331 days	90.68 %
2022	179 kWh	448 kWh	337 days	92.58 %
Average	170 kWh	425 kWh	320 days	87.53 %

The number of days with sufficient surplus energy is the same for both S2-20S and S2-50S in each year. This is because the purification loads are small enough that, when surplus energy is available, it is sufficient to meet either access level. The number of clean water days varies across the years, with a range of 45 days between the lowest and highest performing years. On average, the system supplied clean water on 320 days per year, which corresponds to 87.5 % of the year.

In S2-20S, the difference in annual energy usage between the lowest and highest years is 24 kWh. For S2-50S, the corresponding difference is 60 kWh. These changes reflect year-to-year variation in surplus energy availability.

The consistent number of clean water days across both cases highlights that the system's ability to support surplus-powered purification is driven more by the presence or absence of surplus energy than by the size of the purification load. While some years allow for more reliable purification service than others, the overall coverage remains relatively high in all years, ranging from 80 % to 92.6 %.

To further illustrate this behavior, Figure 4.5 shows the number of days per month with sufficient surplus energy for water purification from 2019 to 2022. Each year is shown in a different color, with 2019 in dark blue, 2020 in light blue, 2021 in pink, 2022 in yellow, and the total number of days in each month overlaid as a dotted line.

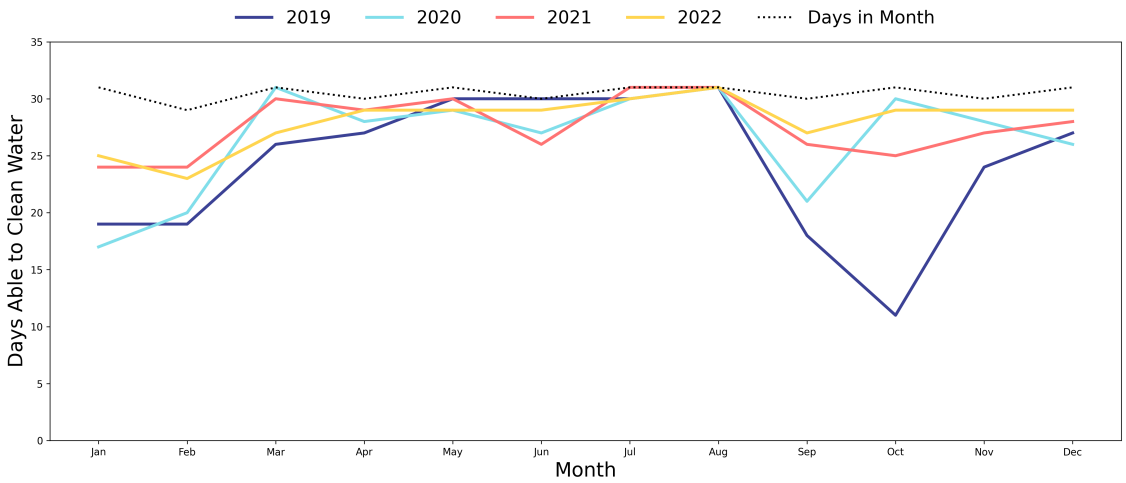


Figure 4.5: Monthly Purification Days [48]

The monthly trends show that the system consistently supports a high number of clean water days between March and August, with most months in this period approaching the maximum days. This indicates that surplus energy availability is generally strong during these months. In contrast, September and October show a clear decline in performance, particularly in 2019 and 2020 when the number of purification days drops significantly. For example, October 2019 recorded fewer than 15 days with sufficient surplus energy. The system typically recovers in November and December with an increase in the number of operational days. This recurring seasonal pattern suggests that surplus energy availability is lower during these months, likely due to reductions in solar energy generation. Despite these temporary dips, the system demonstrates reliable monthly performance across most of the year and confirms its capacity to provide clean water access through surplus-powered purification. Recurring seasonal declines in surplus availability suggest potential periods of limited purification performance that require further investigation to reduce days without sufficient energy for water treatment. Additional strategies, such as small-scale battery storage or complementary energy sources, may be considered to bridge these shortfalls and enhance year-round reliability.

Compared to Table 4.12, which focused on water delivery and energy requirements, Table 4.13 provides additional insight into how effectively the system's capacity is utilised and the associated operational costs under the different access scenarios.

Table 4.13: Annual operation and cost for surplus powered water purification.

Case	System utilisation	UV Energy Used	Dam Annual Cost	Purification Annual Cost	Total Annual Cost
Base	70.89 %	–	$51 127	–	$51 127
S2-20S	70.89 %	170 kWh	$51 127	$9 717	$60 844
S2-50S	70.89 %	425 kWh	$51 127	$24 041	$75 168

Although system utilisation remains constant at 70.89% across all cases, this reflects

the availability of surplus energy rather than variations in purification demand. The additional purification energy use in S2-20S and S2-50S arises because water treatment is restricted to sunlight hours. As a result, the system must purify the same daily water volume within a shorter window, approximately 5 hours per day on average, which requires a purification system capable of handling a higher flow rate and increases the instantaneous energy demand during those periods.

The base case represents the cost of the dam infrastructure without any purification, totaling $51 127 annually. This cost remains unchanged in the surplus-powered scenarios, as no modifications to dam infrastructure are required. Both S2-20S and S2-50S make full use of available surplus energy on days when purification is possible, as shown in earlier results. This indicates that system performance is primarily constrained by surplus energy availability rather than by infrastructure or purification capacity. The approach is energy efficient, as it relies entirely on surplus power that would otherwise go unused.

The purification cost in S2-20S is $1 135 higher than in S2-20C, representing a 13 % increase. In S2-50S, the purification cost exceeds that of S2-50C by $2 585, an increase of 12 %. These differences reflect the higher energy intensity and operational adjustments required to treat water within more constrained surplus periods.

When comparing total system costs, S2-20S is $1 108 more expensive than S2-20C, which corresponds to an increase of 1.9 %. For S2-50S, the total annual cost is $2 415 higher than in S2-50C, a rise of 3.3 %. This demonstrates that surplus-powered purification, although it avoids investment in a turbine, results in moderately higher overall costs. The reason is the limited and concentrated availability of surplus energy, which requires overdimensioning the purification system to meet demand. Even in the highest case, the energy used for purification is less than 0.2 % of the annual pumping energy, highlighting the minimal burden it places on the overall system.

4.6 Scenario 3: Combined Model

This scenario evaluates overall system performance when household electrification and community water purification are delivered simultaneously. It includes supplying purified water to a population of 1565 people and providing electricity to 150 households. Water purification is set at 50 liters per person per day, which represents the higher access level.

The first three electrification tiers from Scenario 1 are included and combined with the 50-liter purification load from Scenario 2. Water purification is powered either by surplus solar energy when available or through a turbine using solar-powered hydro storage. This results in six combined cases: S3-T1-50C, S3-T2-50C, and S3-T3-50C for turbine-powered supply, and S3-T1-50S, S3-T2-50S, and S3-T3-50S for surplus-based supply. Tier 4 is excluded from this scenario, as it was found to be infeasible in Scenario 1 due to high system demands and cost.

4.6.1 Turbine Powered Water Purification Across Tiers 1–3

This configuration evaluates whether the dam system can meet the combined demand of household electricity and water purification using the turbine-based setup. The fixed purification load of 50 liters per person per day is paired with household electricity needs from Tier 1 to Tier 3. The turbine operates as part of a solar-powered hydro storage system, supplying both services through the same infrastructure.

Table 4.14 shows the optimized system capacities for each case, including reservoir volume, pump and solar capacities, and turbine size.

Table 4.14: System component capacities for combined electrification and water purification cases.

Case	Reservoir	Pump	Solar	Turbine
Base	9 119 m^3	265 kW	395 kW	0.00 kW
S3-T1-50C	9 086 m^3	267 kW	401 kW	0.51 kW
S3-T2-50C	8 733 m^3	315 kW	470 kW	7.56 kW
S3-T3-50C	10 145 m^3	441 kW	744 kW	30.06 kW

The combined configuration follows the sizing trends observed in Scenario 1 closely, with only minor increases to account for the electricity required for water purification. In all cases, the addition of water purification results in a uniform increase of 0.06 kW in turbine capacity relative to Scenario 1. However, because purification represents a constant energy demand, its impact is proportionally greater in smaller systems. For example, S3-T1-50C requires a 13.3% larger turbine than S1-T1. In contrast, the same 0.06 kW increase results in only a 0.8% increase in S3-T2-50C and 0.2% in S3-T3-50C.

Pump and solar capacities in Scenario 3 closely mirror those in Scenario 1, with only minimal differences. S3-T1-50C matches S1-T1 exactly in pump capacity and shows a 0.25% increase in solar. In S3-T2-50C, the pump increases by 0.3% and solar by 0.21%. S3-T3-50C again shows no change in pump capacity and only a 0.13% increase in solar. These are all very minor changes, with 0.3% being the largest observed.

These small variations are consistent across tiers and reflect the minor influence of adding a constant purification load to an already electrified system. In systems already sized for higher power delivery, the additional load is easily absorbed without requiring changes to dam infrastructure.

Reservoir capacities in Scenario 3 also follow those in Scenario 1 closely. S3-T1-50C and S3-T2-50C each exhibit a minor decrease of 0.03% compared to their Scenario 1 counterparts, while S3-T3-50C presents a marginal increase of 0.08%. These minimal differences suggest that the inclusion of purification does not significantly affect storage requirements and that operational strategies remain largely consistent with

those in Scenario 1.

Overall, Scenario 3 aligns closely with Scenario 1, with only minimal adjustments needed to support constant low-level water purification. This reinforces the conclusion from Scenario 2 that the energy demand from purification at the 50-liter level has little influence on overall system sizing when integrated into an already electrified setup.

The following table 4.15, summarises annual system utilisation, turbine energy output, and cost components for the combined electrification and water purification cases. It presents the dam system cost, purification cost based on clean water delivery, and resulting total annual cost.

Table 4.15: Annual operation and cost summary for combined electrification and water purification cases.

Case	System utilisation	Turbine Energy (MWh)	Dam Annual Cost	Purification Annual Cost	Total Annual Cost
Base	70.89 %	0 MWh	$51127	$0	$51127
S3-T1-50C	71.33 %	4.4 MWh	$51764	$21456	$73220
S3-T2-50C	77.29 %	66 MWh	$60845	$21456	$82301
S3-T3-50C	82.28 %	263 MWh	$93359	$21456	$114815

System utilisation in Scenario 3 closely matches that of Scenario 1, with only minimal differences across tiers. S3-T1-50C shows a slight increase of 0.06 % compared to S1-T1. S3-T2-50C was 0.03 % higher than S1-T2. S3-T3-50C was 0.01 % lower than S1-T3. These negligible differences confirm that adding water purification does not affect overall system efficiency.

Turbine energy generation also shows only slight increases. S3-T1-50C produces 4.4 MWh, which is 12.8 % more than S1-T1. S3-T2-50C generates 0.74 % more than S1-T2, while S3-T3-50C produces 0.18 % more than S1-T3. These small variations reflect the fixed electricity required for water purification, which becomes increasingly negligible in systems already scaled for household demand.

The dam's annual cost increases with each case in Scenario 3 and remains nearly identical to Scenario 1. S3-T1-50C is 0.1 % more expensive than S1-T1, while S3-T2-50C and S3-T3-50C show no difference. Compared to Scenario 2, the total system cost in Scenario 3 is substantially higher, 236.3 % more in T1, 278.1 % in T2, and 427.4 % in T3. However, this added cost supports both household electrification and water purification, highlighting the efficiency of combining services into a single integrated system.

The purification cost remains fixed at $21456 in all combined scenarios, based on a constant treatment requirement of 50 liters per person per day. Since this load does not change across tiers, its cost contribution is consistent and isolated from other system dynamics.

Total annual cost increases in line with electricity demand. It rises from $73220 in S3-T1-50C to $82301 in S3-T2-50C and reaches $114815 in S3-T3-50C. The cost difference between the base case and S3-T1-50C is $22093. From S3-T2-50C to S3-T3-50C the increase is $32514. These changes are driven almost entirely by expansions in solar and pumping capacity.

These comparisons highlight an important insight. When a system is already designed for household electrification as in Scenario 1, adding water purification imposes only a minimal cost and has negligible impact on system efficiency or sizing. In contrast, starting from a system built solely for water purification as in Scenario 2, expanding it to include electrification results in a substantial increase in cost. This demonstrates the value of integrated planning. Combining services from the outset enables more efficient use of infrastructure and improves overall cost effectiveness.

4.6.2 Surplus-Energy Water Purification Across Tiers 1–3

This configuration evaluates whether surplus solar energy from household electrification can meet the clean water demand of 50 liters per person per day. It uses the same system capacities established in Scenario 1.

Purification is powered exclusively by the solar energy that remains after household and pumping needs are met. The hydro power does not contribute to purification.

The aim is to determine how much of the water treatment requirement can be fulfilled without increasing cost or modifying infrastructure. Table 4.16 presents system utilisation, surplus energy availability, and purification outcomes across tiers.

Table 4.16: Annual operation and cost summary for combined electrification and surplus-powered water purification cases.

Case	System utilisation	Surplus Energy (MWh)	Dam Annual Cost	Purification Annual Cost	Total Annual Cost
Base	70.89 %	154 MWh	$51127	$0	$51127
S3-T1-50S	71.27 %	154 MWh	$51694	$24041	$75735
S3-T2-50S	77.24 %	142 MWh	$60773	$24041	$84814
S3-T3-50S	82.25 %	176 MWh	$93272	$24041	$117313

System utilisation in the surplus powered configuration is identical to Scenario 1 across all tiers. The small energy requirement for purification, at just 0.4 MWh compared to over 140 MWh of available surplus, has no measurable effect on utilisation. This confirms that surplus powered purification does not influence overall system efficiency.

The amount of surplus energy varies across tiers due to differences in household electricity demand. However, the daily pattern of surplus availability remains unchanged, as it always occurs during daylight hours when solar generation exceeds

load. Since the purification process lacks storage, delivery is constrained to these surplus periods. The energy required for purification is so small that total surplus volume is less critical than its daily presence. This behaviour mirrors Scenario 2 but benefits from higher overall surplus due to electrification infrastructure already in place.

The dam's annual cost in S3-T1-50S, S3-T2-50S, and S3-T3-50S remains consistent with Scenario 1, indicating that purification does not influence infrastructure sizing. However, the total annual system cost is significantly higher than in Scenario 2 due to the added electrification components. Purification cost is held constant at $24041 across all tiers, based on treating 50 liters per person per day using available surplus. While this assumes access to solar surplus when needed, actual delivery may vary depending on timing and competing loads.

A more flexible configuration could prioritise solar surplus for purification and allow the turbine to supplement purification energy when solar is insufficient. Given the small size of the purification load, this would require only a minor reduction in household electricity on occasional days while improving reliability of water treatment.

5

Discussion

The simulations conducted in this study were based on four years of TAHMO weather data collected from the College de Rushaki station, covering the period from 2019 to 2022. This dataset provided an initial understanding of seasonal irrigation patterns and system behavior. However, the limited duration of the data made it difficult to draw strong long-term conclusions. Differences in rainfall and temperature from year to year influenced optimal system capacities, and four years of data were not sufficient to identify consistent trends or account for extreme climate conditions. Nevertheless, the model developed in this project was flexible and could be used with a longer time series in future studies. With more extensive data, it would be possible to carry out a more detailed and statistically reliable analysis, which would enhance the accuracy of system design recommendations.

The main goal of this project was to develop a sustainable and practical solution to meet the combined needs for irrigation, electricity, and clean water. A simple design was central, as complex systems can be expensive and difficult to maintain, especially in rural areas or regions with limited resources. The idea of a multipurpose dam played an important role in responding to these challenges. Rather than focusing on the irrigation system alone, the aim was to create synergies between different parts of the system, allowing surplus energy to be used in meaningful ways. By integrating multiple functions, the system also gained flexibility to accommodate future energy needs, which may differ from current demand. This underscores the value of a modular approach, where infrastructure can grow over time in response to evolving community priorities and improve long-term efficiency. Future research could explore how to make better use of the solar surplus energy generated by the system. Potential extensions might include the integration of battery storage to increase flexibility or connecting the system to community services. These additions could enhance the overall utility of the dam infrastructure and support broader rural development goals.

More broadly, the model's narrow cost-based focus may overlook critical aspects of sustainability and social acceptability. Designing infrastructure based solely on economic efficiency can lead to solutions that are misaligned with local values, environmental priorities, or long-term resilience. Factors such as the environmental impact of component manufacturing, the ecological footprint of dam construction, and the inclusion of local communities in planning and decision-making are essential to sustainable infrastructure. While difficult to quantify in linear programming, these considerations are central to real-world implementation and should be inte-

grated into future planning efforts.

5.1 Discussion of Results

The following sections discuss the findings from the four-year simulation period in more detail. Although the dataset was limited in scope, it still provided valuable insights into how the system behaved under varying seasonal and annual conditions.

5.1.1 Crop Water Requirements and Irrigation Needs

The irrigation demand observed across the four-year simulation period showed clear seasonal patterns and moderate year to year variability. While peak irrigation volumes generally occurred during the dry seasons when effective rainfall was low, the absolute values differed between years. For example, January showed the highest demand in 2019, while the autumn months were more critical in later years. These trends indicated that irrigation needs were sensitive not only to crop schedules but also to interannual weather fluctuations.

This variability presented challenges when designing irrigation infrastructure, as effective rainfall was highly inconsistent, with rainfall during dry months being up to 90% lower than during rainy periods. As a result, relying too heavily on rainfall contribution could have compromised water availability during critical growth phases. A more robust design approach would involve planning for peak-year or percentile-based demand scenarios to ensure system reliability under more extreme conditions.

Several assumptions reduced the general applicability of the model. The analysis relied on data from a single weather station located near, but not at, the actual site. This may not have accurately reflected local microclimatic effects, particularly in hilly or varied terrain as in Tabagwe. Installing a dedicated weather station at the site and collecting data across all seasons would have significantly improved model accuracy and calibration.

A fixed crop schedule was assumed for calculating crop water requirements, which may result in a lock-in effect. While this provided a baseline, it may not have reflected how farmers actually adapted planting times or crop selection in response to local conditions and market factors. Additionally, further studies could explore ways to reduce this lock-in by developing more flexible system configurations. Future work could explore the impact of varying crop combinations and planting calendars to identify more resilient or efficient system. This would reduce the risk of over or under dimensioning the system for a single fixed case and support the development of more adaptive and scalable designs.

5.1.2 Base Model: Irrigation Dam

The base model was developed to meet crop water demand using site-specific parameters and weather data. Reservoir volume, pump size, and solar capacity were determined through cost minimisation, resulting in a functional configuration that prioritised affordability over energy efficiency.

Solar utilisation averaged 71 %, with surplus energy typically occurring when the pump operated at full capacity or the reservoir was near full. This reflects a tradeoff between ensuring reliability and maximising energy use. Options to reduce surplus include adding a generator for peak periods, which could allow downsizing the solar array, or storing excess energy in batteries. However, batteries would need to be large to absorb short, high-output bursts, increasing cost and complexity. At the same time, previous studies have shown that using only water storage instead of batteries can reduce both installation and maintenance costs while maintaining system performance [14]. This highlights the importance of evaluating not just the energy balance, but the cost-effectiveness of different storage strategies. It also underscores the importance of considering how surplus energy can be utilised effectively. Alternatively, surplus energy could potentially be redirected to community use or grid sale. While infrastructure is not currently in place, future integration could increase system value without altering the irrigation design.

Cost analysis showed that the reservoir, though over 9 000 m^3 and serving 88 hectares, contributed less than 3 % of annualised cost. The pump and solar array dominated expenses, suggesting greater efficiency gains can be achieved by improving the coordination of energy supply and use. The assumed head height of 130 metres was based on early estimates.A lower head of 70 metres could offer similar performance at reduced energy cost. Since lifting water to a lower height requires less potential energy, the same volume can be delivered using a smaller pump and reduced solar capacity, significantly lowering system costs. The chosen site prioritised accessibility and avoided local disruption, showing that dam siting is both a technical and acceptability-driven design factor.

Future improvements should align energy generation more closely with demand and allow for greater flexibility in siting and infrastructure. These adjustments could improve efficiency without raising overall cost.

5.1.3 Scenario 0: Average vs. Yearly Variability

Scenario 0 examined how system sizing would differ if each year were modelled independently. Reservoir volumes varied by a factor of more than 2.5 across the four years, while pump capacities differed by nearly 70 kW, representing over a 30 % increase from the lowest to the highest value. Solar PV sizing was more stable, showing a spread of about 60 kW, which corresponds to an increase of roughly 20 %. The year-to-year differences reflected shifts in rainfall patterns and irrigation demand. Some years required larger reservoirs, while others needed more energy for pumping. To avoid under- or over-dimensioning the system due to these annual fluctuations,

the Base Case was defined by averaging the cost-optimal capacities. This configuration proved robust, fulfilling over 97 % of irrigation demand in every year.

Although the Base Case was formed by averaging the cost optimal solutions from each year, it still performed reliably when applied back to the individual years using fixed Base Case capacities. This suggests that the average sizing was not highly sensitive to yearly variation and provided a balanced result.

Performance did not always correspond to component size. In 2021, the smallest system met all demand with the highest energy use efficiency. In 2022, larger capacities delivered lower performance. This indicates that timing and distribution of demand and supply are often more important than total size.

When the Base Case capacity configuration was applied across all years, the irrigation demand was met on nearly all days. The observed deficits were minor, and in 6 out of the 14 deficit days, the reservoir volume had even increased by the end of the day. This indicates that water was available but not utilised effectively due to operational constraints. Two potential strategies could help mitigate these shortfalls, implementing a more flexible irrigation schedule. However, this would require manual intervention or a more advanced control system, allowing daily irrigation needs and system boundaries to be adjusted dynamically rather than relying on a fixed, automatic schedule.

Designs based on years like 2021 or 2022 would have reduced cost by up to \$5 000 annually but would not perform well in other years. This shows the tradeoff between cost and reliability. While averaging is effective, using median or percentile sizing may better reflect extreme conditions.

Previous studies have shown that even limited access to irrigation can lead to improved crop yields [11]. Therefore, although the model includes some shortfalls between estimated crop water needs and actual irrigation, these are unlikely to have a major impact on overall yield. On average, the Base Case system is still expected to support productivity gains, even if occasional deficits occur. The overall annual coverage was therefore deemed sufficient to proceed with integrating electricity generation and water purification into the dual- and multipurpose system configurations based on the average output capacities of the Base Model.

5.1.4 Scenario 1: Household Electrification

Adding household electricity demand to the irrigation system significantly influenced system sizing and energy use. S1-T1 introduced basic access with minimal cost increase, while S1-T2 and S1-T3 required progressively larger expansions in pump and solar capacities. S1-T4, led to a disproportionately large increase in system size and cost, marking the point where electricity demand began to exceed what the original configuration could efficiently support.

S1-T1 resulted in only a slight increase in system size. Pump and solar capacities rose by less than 1%, and the reservoir volume remained stable. A small turbine was introduced at minimal cost, enabling the delivery of nearly 4 MWh annually to 150 households. This tier provided a cost-effective entry point for electrification, with almost no disruption to existing infrastructure.

S1-T2 required approximately 19% more pump and solar capacity and added a mid-sized turbine. The total cost increased by nearly $10 000, yet the turbine's rated output exceeded the minimum requirement by a factor of six resulting in an energy output of 66 MWh annually. This highlights an essential design feature, even when the system is sized to meet a basic electricity tier, the rated capacity often allows significantly more energy to be delivered than strictly required.

S1-T3 extended electricity delivery hours and required substantial system expansion. Pump capacity increased by 67% and solar capacity by 88% compared to the Base Case. The turbine capacity rose to 30kW, four times larger than in S1-T2 with an anually rated turbine output of 263 MWh. This tier achieved the highest system utilisation at 82.3% indicating efficient use of available energy. However, surplus energy also rose to 176MWh, suggesting that the system had to be oversized to maintain consistent electricity delivery throughout the day. While technically effective, this configuration introduced higher costs and surplus, reflecting the trade-offs involved in scaling up energy access within the existing system design.

S1-T4 marked a break from the previous progression, with a disproportionately large increase in solar and pump capacity, as well as overall cost. While the reservoir volume decreased only slightly, pump capacity rose by 142 %, and solar PV capacity increased by more than 3 435 %. The total system cost rose by over 2 360 %, primarily driven by the scale of the solar installation. System utilisation dropped to just 13 %, and energy surplus reached 16 476 MWh, more than 100 times that of the Base Case. The findings highlight a design threshold beyond which the current system loses efficiency, indicating that accommodating electricity demand at this scale requires a fundamentally redesigned approach.

These results show that higher tiers enable greater electrification but place increasing strain on solar and pumping infrastructure. Since turbine generation depends entirely on water lifted by solar-powered pumps, electricity delivery amplifies energy demand without increasing irrigation. While S1-T1 to S1-T3 offer technically viable configurations under current assumptions, each reflects a trade-off between cost, service level, and long-term flexibility. S1-T1 offers low-impact, near cost-neutral access. S1-T2 balances affordability with capability. S1-T3 provides significantly expanded access at a much higher cost. S1-T4, although theoretically possible, highlights the limits of the existing design and would necessitate a new system architecture to operate efficiently.

While this analysis compares costs across configurations, it is important to recognise that different levels of electricity access also provide varying degrees of social and

economic value. For example, S1-T1 and S1-T2 offer around 4 hours of electricity per day, whereas S1-T3 and S1-T4 provide 8 and 16 hours, respectively. The available power capacity also plays a crucial role in determining the range of household uses, such as whether it supports only basic needs like lighting and phone charging or extends to appliances like televisions and refrigerators. A more comprehensive evaluation of the higher tiers could include comparison with the cost of expanding the national grid, reflecting both economic and developmental considerations. This broader perspective could be explored in future studies.

5.1.5 Scenario 2: Water Purification

Water purification was integrated with negligible impact on dam infrastructure. The additional load was small and did not require system resizing, which demonstrates technical feasibility. However, despite its low energy demand, UV-based purification introduced a significant cost increase due to the high capital cost of the lamps themselves.

In Scenario S2-50C, which represents the highest turbine demand case, the energy used for purification was less than 0.2 % of the annual pumping energy. This indicates that the turbine contributes only marginally to the overall operational load. The associated cost increased the dam's annual cost by just 0.3%, indicating that turbine-based water treatment can be implemented with minimal impact on dam infrastructure and operating expenses.

However, despite its low energy demand, UV-based purification introduced a significant cost increase due to the high capital cost of the lamps. Compared to the base case, total annual system costs rose by 17 % in S2-20C and by 42 % in S2-50C. The purification cost itself was 150 % higher in S2-50C than in S2-20C, consistent with the increase in clean water demand. These results show that the primary limitation lies not in system energy supply but in the cost structure of the purification technology.

The surplus-powered purification configuration allowed for the integration of clean water services without altering the system's core design. This approach took advantage of otherwise unused energy and demonstrated high energy efficiency. However, while conceptually attractive, it required purification systems to operate at higher intensity during short windows of energy availability. As a result, it could not guarantee daily water delivery, making it less suitable for essential services with continuous demand. This reinforces the broader observation that surplus energy is best applied to flexible or supplementary uses, while services such as drinking water require stable and predictable energy sources.

In S2-20S and S2-50S, the total annual costs were \$1 108 and \$2 415 higher than in their constant-powered counterparts, representing increases of 1.9 % and 3.3 %, respectively. Despite avoiding infrastructure upgrades, surplus-powered purification resulted in moderately higher costs due to limited and irregular energy availability.

Clean water could not be delivered consistently, making the approach less reliable and suited to services with continuous demand unless supported by additional design measures.

In all surplus cases, the model prioritised irrigation first, using only remaining solar energy for purification. This raises the question of whether a greater share of clean water demand could have been met if the prioritisation were reversed. A possible alternative to address these shortfalls involves supplementing supply on non-operational days through bottled water or chemical disinfection methods such as chlorination. Although this may place a financial burden on individuals, covering only around 45 days of the year is considerably more affordable than relying on purchased or treated water every day. Another strategy could involve increasing water purification production when energy is available and storing the treated water in an auxiliary tank to serve as a buffer during periods of low energy availability. Alternatively, battery storage could be integrated to sustain purification during times when surplus energy is insufficient. Each of these strategies carries distinct implications for cost, complexity, and reliability, and warrants further investigation to assess their feasibility. Future studies could explore alternative strategies to better balance or maximise delivery of multiple services within the same system.

The turbine-powered configurations, by contrast, delivered full clean water coverage with only marginal cost increases, offering a more reliable and cost-effective solution. These results highlight a clear trade-off. Surplus energy can be used to improve system value but cannot alone guarantee service reliability for critical uses like water treatment.

This Scenario explored one technically feasible treatment approach that has been used in rural settings. However, other purification methods, such as chlorination or decentralised systems, may offer greater cost-effectiveness. Since surplus energy exists in the system, more energy-intensive alternatives could be justified if they improve economic performance overall. The analysis does not define acceptable access levels but outlines the system and cost implications of different configurations. Final decisions on service provision remain with future stakeholders.

5.1.6 Scenario 3: Combined Model

Delivering both household electricity and clean water in a combined system proved technically feasible. The infrastructure sizing scaled with the electricity load, while the water purification load had minimal impact through all cases. In turbine-powered configurations, the energy for UV purification was absorbed efficiently, adding a fixed operational cost but no significant design burden. The results closely mirrored findings from Scenarios 1 and 2, confirming that the individual system components interact in a stable and predictable manner when combined.

Adding water purification on top of the electrification tiers resulted in a uniform increase of 0.06 kW in turbine capacity. This corresponded to a 13.3 % turbine ca-

pacity increase in S3-T1-50C, while in S3-T3-50C the same increase was negligible by comparison. These differences show that fixed loads like purification have a more noticeable impact in smaller systems. In S3-T3-50C, the pump and solar capacities differed by less than 0.3 % from S1-T3 values, confirming that purification demand had negligible influence on infrastructure sizing.

System utilisation increased with each access tier, driven primarily by rising electricity generation. While the extended electricity generation resulted in higher costs, the cost of water purification remained fixed across all cases. This predictability simplifies cost planning but also highlights that the main financial burden stems from the purification technology rather than from energy or infrastructure constraints.

In surplus-powered configurations, clean water services were delivered without altering core system design. The surplus energy approach used otherwise unused capacity efficiently but could not guarantee daily delivery. This limits its suitability for services requiring continuous supply. Notably, the dam's annual cost in S3-T1-50S, S3-T2-50S, and S3-T3-50S remained consistent with Scenario 1, indicating that the surplus-powered purification had no effect on infrastructure sizing. However, total annual system cost was significantly higher than in Scenario 2 due to the added electrification components. Purification cost remained fixed at $24,041 across all tiers, based on delivering 50 L per person per day using available surplus. While this assumes regular access to solar surplus, actual delivery may vary depending on timing and competing system loads.

A more flexible configuration could prioritise solar surplus for purification and allow the turbine to supplement water treatment when solar is insufficient. Given the small purification load, this would require only minor reductions in household electricity on occasional days while improving reliability. This raises a broader point. When starting from an electrified system, as in Scenario 1, adding purification services requires minimal cost and has negligible impact on sizing or performance. In contrast, expanding a water purification system, as in Scenario 2, to include electrification results in a major cost increase. These comparisons demonstrate the value of integrated planning. Designing systems to deliver multiple services from the outset allows for more efficient use of infrastructure and improves overall cost-effectiveness.

5.2 Societal Aspects

This thesis aligns with several Sustainable Development Goals (SDGs), including Zero Hunger, Clean Water and Sanitation, Affordable and Clean Energy, and Climate Action. While technological innovation plays a key role in improving living standards and driving economic development in rural areas, it also introduces challenges that must be considered.

Conducting this study within a cultural context unfamiliar to the authors presents certain challenges. As researchers without prior experience in the Rwandan setting, there is a risk that some assumptions may have been overly simplified or aspects of

the local context misinterpreted. The authors acknowledge these limitations with humility and recognise that cultural, institutional, and social nuances may not have been fully captured. Such inaccuracies could potentially influence the analysis and the relevance of proposed solutions.

Scenario 1 explores electricity generation at different capacity levels, where larger capacities could enable households to engage in income generating activities (IGAs). During the field study, many households expressed a desire for electricity access specifically to support small business development. Notably, a majority of respondents mentioned similar types of IGAs. Previous studies have shown that rural business expansion can be challenging and that an oversaturation of similar IGAs may lead to economic inefficiencies or losses. To avoid such outcomes, higher tiers of electricity access could beneficially be accompanied by measures that encourage diversification and support the long-term viability of local enterprises.

In Scenario 2, the integration of water purification demonstrates both potential and vulnerability. The system incurs high annual costs and relies on purification units that must be replaced either annually or every 5.25 years, depending on the operation mode. This creates a situation of dependency, where local residents are reliant on continued investment from external stakeholders. If funding or institutional support is not maintained, access to clean water may be lost, potentially reversing development progress.

Moreover, the surplus-powered purification option results in an intermittent water supply, as it only functions on days with excess energy availability. While alternative solutions such as bottled water or chlorination could complement the system, they introduce additional financial burdens for households that may already face economic hardship. Ensuring the long-term sustainability of such interventions requires not only technical feasibility but also institutional, economic, and community support mechanisms.

The authors are deeply grateful for the opportunity to carry out this study in Rwanda and wish to express their sincere respect for the people involved. Although the study was approached with care and the intention to contribute meaningfully, the authors are aware that they do not have a local background. As such, the authors do not claim to fully understand all cultural, social, or institutional nuances, and recognise that important details may have been missed. This is not due to a lack of interest or concern, but simply a reflection of the limits that come with working in a setting that is not one's own. Some communication also relied on a translator, which may have introduced misunderstandings as the information passed through an additional person. The authors have tried their best to listen, learn, and represent the setting with honesty and thoughtfulness. It is important for readers to keep in mind that the authors write as external researchers, aware of their inevitable ignorance, but who endeavoured to conduct the work with appropriate humility.

6

Conclusion

A multipurpose dam system integrating irrigation, household electricity, and clean water is technically and economically feasible for Tabagwe. All three services were successfully combined into a solar-powered pumped hydro system, and performance remained stable across configurations. Cost-effectiveness depends on the service level provided. Basic electricity access levels can be added with modest investment, while higher tiers require significantly more infrastructure and cost.

A single-purpose irrigation system was developed using a 9 119 m^3 reservoir, a 265 kW pump, and a 395 kW solar array. The total annual cost was \$51 127. The system achieved high solar utilisation and met agricultural water demand with minimal shortfalls, demonstrating effective performance under current weather conditions.

Analysis of four years of weather data revealed that interannual variability significantly influenced optimal system sizing. Reservoir requirements ranged from under 5 800 to over 14 500 m^3. Despite these variations, the average base configuration performed reliably in all years. This confirms that using multi-year data improves robustness without substantial oversizing.

Adding household electricity access was technically viable across all tiers. Tier 1 required only minor infrastructure changes and increased cost by less than 2 %. This means that if the dam is built primarily for irrigation, adding Tier 1 access has minimal impact on cost and infrastructure while enabling around four hours of electricity per day to households that currently have none. Tiers 2 and 3 introduced substantial expansions in pump and solar capacity, raising costs by approximately \$9 600 and \$42 000 respectively. These tiers provide increasing levels of social and economic value through longer electricity access and support for more household appliances Tier 4, however, led to a sharp increase in infrastructure and cost, indicating that the current system design is not well suited to support this level of electricity access.

Water purification using ultraviolet treatment was technically feasible and required no resizing of the dam infrastructure. Although energy demand was low, the capital cost of the purification system was high. The annual purification cost reached \$21 456, representing nearly 40 % of the total cost of the irrigation-only system. The approach is viable but financially demanding.

When all services were combined into a multipurpose system, infrastructure scaled predictably. Electricity access remained the primary driver of system cost, while

water purification contributed a fixed and independent cost component. The most advanced configuration, which included Tier 3 electricity and 50 liters of clean water per person per day, resulted in a total annual cost of $114 729.

Although the multipurpose system achieved high utilisation, it still produced a substantial surplus of solar energy. To increase system efficiency and better utilise this excess energy need further investigation into how this surplus can be better utilised or stored could enhance overall system efficiency.

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A

Appendix

The crop coefficient values for the three crops used in this thesis are displayed in Table A.1. The operational and economic parameters are provided in Appendix A.2, while the optimization model and constraints are described in detail in Appendix A.3.

Table A.1: Crop coefficient values for different crop types

Crop Type	$K_{c,\max}$
Banana	1.2
Maize	1.2
Beans	1.15

A.2 Code Parameters

```
# Physical constants
gravity = 9.81  # m/s2
water_density = 1000  # kg/m
static_head = 100  # meters
pipe_fricition = 0.3
total_dynamic_head = static_head * (1+pipe_fricition) #meters

# System parameters
initial_volume_in_storage = 2000  # m
pump_efficiency = 0.7
solar_efficiency = 0.2
bio_efficiency = 0.35
turbine_efficiency = 0.85  # Efficiency of hydro turbine
m2_per_kwp = 5  # m2/kWp
bio_fuel_cost = 0.33  # $/kWh

# Cost parameters
capex = {
    'solar': 758,  # $/kW
    'bio': 665,    # $/kW
    'pump': 400,   # $/kW
    'dam': 1.22,   # $/m
```

```
    'turbine': 400   # $/kW
}

opex = {
    'solar': 0.05,   # % of annual investment
    'bio': 0.05,     # % of annual investment
    'pump': 0.05,    # % of annual investment
    'dam': 0.05,     # % of annual investment
    'turbine': 0.025  # % of annual investment
}

crf = {
    'solar': 0.0651,
    'bio': 0.0710,
    'pump': 0.0963,
    'dam': 0.0548,
    'turbine': 0.0872
}

# Time parameters
annual_hours = 8760

# Clean water production parameters
CLEAN_WATER_PARAMS = {
    'energy_per_m3': 0.017,
    'capex_per_m3_day': 0.1371,
    'opex_rate': 0.1371,
    'crf': 0.065,
    'lifetime': 1
}
```

Listing A.1: System Parameters Used in Analysis

A.3 Solar-Powered Irrigation Optimization Model Code

```
"""
Solar-powered irrigation system optimization model.
This script optimizes the sizing of a solar-powered
   irrigation system with water storage,
minimizing total annual costs while meeting irrigation
   demands.
"""

import pyomo.environ as pyomo
import pandas as pd
import matplotlib.pyplot as plt
```

```
from pyomo.opt import SolverFactory
from pathlib import Path
from chart_config import configure_chart, configure_subplot, save_plot, finalize_layout, COLORS, LINE_STYLES
from parameters import (
    gravity,
    water_density,
    total_head,
    pump_efficiency,
    solar_efficiency,
    initial_volume_in_storage,
    capex,
    opex,
    crf,
    annual_hours,
    m2_per_kwp
)

# Load and process irrigation demand data
irrigation_path = '2_fao/5_irrigation_requirement/5_irrigation_schedule/irrigation_schedules/2022.csv'
irrigation = pd.read_csv(irrigation_path)
hourly_irrigation_volume = irrigation['irrigation_volume [m]'].values

# Load and process solar radiation data
solar_path = '1_annual/yearly_data_TAHMO/2022.csv'
solar = pd.read_csv(solar_path)
solar['datetime'] = pd.to_datetime(solar['Date'] + ' ' + solar['Time'])
solar.set_index('datetime', inplace=True)

# Convert solar radiation to energy generation potential
solar['kwh_per_kwp'] = (solar['radiation AVG (W/m2)'] * m2_per_kwp) / 1000

# Prepare time series data for optimization model
irrigation_requirement = {t+1: hourly_irrigation_volume[t] for t in range(annual_hours)}
solar_available = {t+1: solar['kwh_per_kwp'].iloc[t] for t in range(annual_hours)}

# Initialize optimization model
model = pyomo.ConcreteModel()
model.time_steps = pyomo.RangeSet(1, annual_hours)

# Decision Variables
model.installed_capacity = pyomo.Var(domain=pyomo.NonNegativeReals)  # Solar PV capacity [kW]
```

```
model.storage_water_level = pyomo.Var(model.time_steps,
    domain=pyomo.NonNegativeReals)  # Water storage level [m
    ]
model.water_pumped_into_storage = pyomo.Var(model.time_steps,
     domain=pyomo.NonNegativeReals)  # Pumping rate [m  /h]
model.storage_capacity = pyomo.Var(domain=pyomo.
    NonNegativeReals)  # Reservoir capacity [m  ]
model.pump_power_capacity = pyomo.Var(domain=pyomo.
    NonNegativeReals)  # Pump power rating [kW]

# Cost Variables
model.annual_capital_cost = pyomo.Var(domain=pyomo.
    NonNegativeReals)  # Annualized capital costs
model.annual_operating_cost = pyomo.Var(domain=pyomo.
    NonNegativeReals)  # Annual operating costs
model.solar_system_cost = pyomo.Var(domain=pyomo.
    NonNegativeReals)  # Solar system total cost
model.pump_system_cost = pyomo.Var(domain=pyomo.
    NonNegativeReals)  # Pump system total cost
model.storage_system_cost = pyomo.Var(domain=pyomo.
    NonNegativeReals)  # Storage system total cost

# Objective: Minimize total annual cost
model.objective = pyomo.Objective(
    expr=model.annual_capital_cost + model.
       annual_operating_cost,
    sense=pyomo.minimize
)

# Energy conversion factor for pumping calculations [kWh/m  ]
energy_factor = (water_density * gravity * total_head) /
    pump_efficiency / 3600000

# --- Model Constraints ---

# Storage balance: Water level at t = Water level at t-1 +
    Pumped - Irrigation
model.storage_level_constraint = pyomo.ConstraintList()
model.storage_level_constraint.add(model.storage_water_level
    [1] == initial_volume_in_storage)
for t in range(2, annual_hours + 1):
    model.storage_level_constraint.add(
        model.storage_water_level[t] == model.
           storage_water_level[t - 1] +
        model.water_pumped_into_storage[t] -
           irrigation_requirement[t]
    )

# Storage capacity limits: 10% to 100% of capacity
```

```
model.storage_capacity_constraint = pyomo.ConstraintList()
for t in model.time_steps:
    model.storage_capacity_constraint.add(model.
       storage_water_level[t] <= model.storage_capacity)
    model.storage_capacity_constraint.add(model.
       storage_water_level[t] >= model.storage_capacity *
       0.1)

# Energy balance: Pumping energy cannot exceed solar
   generation
model.demand_constraint = pyomo.ConstraintList()
for t in model.time_steps:
    model.demand_constraint.add(
        model.water_pumped_into_storage[t] * energy_factor <=
        model.installed_capacity * solar_available[t] *
           solar_efficiency
    )

# Pump capacity constraint: Pump power must meet maximum
   pumping rate
model.pump_constraint = pyomo.ConstraintList()
for t in model.time_steps:
    model.pump_constraint.add(
        model.pump_power_capacity >= model.
           water_pumped_into_storage[t] * energy_factor
    )

# Cost calculation constraints
model.capex_constraint = pyomo.ConstraintList()
model.capex_constraint.add(
    model.annual_capital_cost ==
    model.installed_capacity * capex['solar'] * crf['solar']
       +
    capex['pump'] * model.pump_power_capacity * crf['pump'] +
    capex['dam'] * model.storage_capacity * crf['dam']
)

# Component-specific cost calculations
model.capex_constraint.add(
    model.solar_system_cost ==
    model.installed_capacity * capex['solar'] * crf['solar']
       +
    model.installed_capacity * capex['solar'] * opex['solar']
)
model.capex_constraint.add(
    model.pump_system_cost ==
    capex['pump'] * model.pump_power_capacity * crf['pump'] +
    model.pump_power_capacity * capex['pump'] * opex['pump']
)
```

```
model.capex_constraint.add(
    model.storage_system_cost ==
    capex['dam'] * model.storage_capacity * crf['dam'] +
    model.storage_capacity * capex['dam'] * opex['dam']
)

# Operating cost calculation
model.opex_constraint = pyomo.ConstraintList()
model.opex_constraint.add(
    model.annual_operating_cost ==
    model.installed_capacity * capex['solar'] * opex['solar'] +
    model.pump_power_capacity * capex['pump'] * opex['pump'] +
    model.storage_capacity * capex['dam'] * opex['dam']
)

# Solve optimization model
solver = SolverFactory('cbc')
results = solver.solve(model, tee=True)

# Process and display results
print("\nOptimization Results (Solar Only):")
print(f"Status: {results.solver.status}")

if results.solver.status == 'ok':
    print(f"\nOptimal System Capacities:")
    print(f"  Reservoir Capacity: {model.storage_capacity.value:.2f} m  ")
    print(f"  Pump Power: {model.pump_power_capacity.value:.2f} kW ({model.pump_power_capacity.value / 0.746:.1f} HP)")
    print(f"  Solar Power Capacity: {model.installed_capacity.value:.2f} kW")

    # Calculate resulting costs
    dam_capex_val = model.storage_capacity.value * capex['dam']
    pump_capex_val = model.pump_power_capacity.value * capex['pump']
    solar_capex_val = model.installed_capacity.value * capex['solar']

    dam_opex_val = dam_capex_val * opex['dam']
    pump_opex_val = pump_capex_val * opex['pump']
    solar_opex_val = solar_capex_val * opex['solar']

    dam_annual_val = dam_capex_val * crf['dam']
    pump_annual_val = pump_capex_val * crf['pump']
```

```
164     solar_annual_val = solar_capex_val * crf['solar']
165
166     total_annual_capex_val = dam_annual_val + pump_annual_val
            + solar_annual_val
167     total_annual_opex_val = dam_opex_val + pump_opex_val +
            solar_opex_val
168     total_annual_cost_val = total_annual_capex_val +
            total_annual_opex_val
169
170     print(f"\nCost Breakdown (Annualized):")
171     print(f"  Dam: ${dam_annual_val:.2f} (CAPEX) + ${
            dam_opex_val:.2f} (OPEX) = ${(dam_annual_val +
            dam_opex_val):.2f}/year")
172     print(f"  Pump: ${pump_annual_val:.2f} (CAPEX) + ${
            pump_opex_val:.2f} (OPEX) = ${(pump_annual_val +
            pump_opex_val):.2f}/year")
173     print(f"  Solar: ${solar_annual_val:.2f} (CAPEX) + ${
            solar_opex_val:.2f} (OPEX) = ${(solar_annual_val +
            solar_opex_val):.2f}/year")
174     print(f"Total Annual Cost: ${total_annual_cost_val:.2f}/
            year")
175
176     print(f"\nSystem Operation Summary:")
177     dam_cap_val = model.storage_capacity.value
178     storage_percent = (model.storage_water_level[1].value /
            dam_cap_val * 100) if dam_cap_val > 0 else 0
179     print(f"  Optimal Water Level at Start/End: {model.
            storage_water_level[1].value:.2f} m   ({
            storage_percent:.1f}% of capacity)")
180
181     total_water_pumped = sum(model.water_pumped_into_storage[
            t].value for t in model.time_steps)
182     total_irrigation_need = sum(hourly_irrigation_volume)
183     print(f"  Total Annual Water Pumped: {total_water_pumped
            :.2f} m   (Demand: {total_irrigation_need:.2f} m  )")
184
185     total_solar_gen = sum(model.installed_capacity.value *
            solar_available[t] * solar_efficiency for t in model.
            time_steps)
186     total_pump_energy = sum(model.water_pumped_into_storage[t
            ].value * energy_factor for t in model.time_steps)
187     print(f"  Total Annual Solar Generation: {total_solar_gen
            :.2f} kWh")
188     print(f"  Total Annual Pumping Energy: {total_pump_energy
            :.2f} kWh")
189
190     # Calculate energy usage breakdown
191     solar_direct_use_total = sum(model.installed_capacity.
            value * solar_available[t] * solar_efficiency for t in
```

```
        model.time_steps)
192
193     if total_solar_gen > 0:
194         solar_pump_perc = solar_direct_use_total /
               total_solar_gen * 100
195         print(f"  Solar Energy Use: {solar_pump_perc:.1f}%
               Direct to Pump")
196     else:
197         print("  Solar Energy Use: 0% (No solar generation)")
198
199     # --- Plotting ---
200     configure_chart(figsize=(15, 12))
201
202     # Calculate hourly values and convert to daily by summing
            each 24 hours
203     n_days = annual_hours // 24
204     daily_solar = []
205     daily_pumped = []
206     daily_pump_demand = []
207     daily_storage = []
208     daily_irrigation = []
209
210     for day in range(n_days):
211         start_hour = day * 24 + 1
212         end_hour = start_hour + 24
213
214         # Sum solar generation for the day
215         solar_day = sum(model.installed_capacity.value *
               solar_available[t] * solar_efficiency
216                         for t in range(start_hour, end_hour))
217         daily_solar.append(solar_day)
218
219         # Sum water pumped for the day
220         pumped_day = sum(model.water_pumped_into_storage[t].
               value for t in range(start_hour, end_hour))
221         daily_pumped.append(pumped_day)
222
223         # Calculate average storage for the day
224         storage_day = max(model.storage_water_level[t].value
               for t in range(start_hour, end_hour))
225         daily_storage.append(storage_day)
226
227         # Sum irrigation for the day
228         irrigation_day = sum(hourly_irrigation_volume[t-1]
               for t in range(start_hour, end_hour))
229         daily_irrigation.append(irrigation_day)
230
231         # Sum pump demand for the day
```

```
232         pump_demand_day = sum(model.water_pumped_into_storage
                [t].value * energy_factor for t in range(
                start_hour, end_hour))
233         daily_pump_demand.append(pump_demand_day)
234
235     # 1. Stored Water
236     plt.subplot(2, 2, 1)
237     daily_storage_max = []
238     daily_storage_min = []
239     for day in range(n_days):
240         start_hour = day * 24 + 1
241         end_hour = start_hour + 24
242         values = [model.storage_water_level[t].value for t in
                range(start_hour, end_hour)]
243         daily_storage_max.append(max(values))
244         daily_storage_min.append(min(values))
245
246     plt.plot(range(1, n_days + 1), daily_storage_max, label='
            Daily Max Storage', color=COLORS['navy_blue'])
247     plt.plot(range(1, n_days + 1), daily_storage_min, label='
            Daily Min Storage', color=COLORS['light_blue'])
248     plt.fill_between(range(1, n_days + 1), daily_storage_min,
             daily_storage_max, color=COLORS['light_blue'], alpha
            =0.3)
249     plt.axhline(y=model.storage_capacity.value, color=COLORS
            ['black'], linestyle='--', label='Reservoir Capacity')
250     plt.title('Stored Water')
251     plt.ylabel('Volume (m )')
252     plt.xlabel('Day of Year')
253     plt.grid(True)
254     plt.legend(loc='upper center', bbox_to_anchor=(0.5, 0.95)
            , fontsize=9, ncol=1)
255
256     # 2. Water Pumped vs Irrigation Need
257     plt.subplot(2, 2, 2)
258     plt.plot(range(1, n_days + 1), daily_irrigation, color=
            COLORS['light_green'], linewidth=1, label='Irrigation
            Need')
259     plt.plot(range(1, n_days + 1), daily_pumped, color=COLORS
            ['grey'], linewidth=1, alpha=0.8, label='Water Pumped
            ')
260     plt.title('Daily Water Pumped vs Irrigation Need')
261     plt.ylabel('Volume (m /day)')
262     plt.xlabel('Day of Year')
263     plt.grid(True)
264     plt.legend(loc='upper center', bbox_to_anchor=(0.5, 0.95)
            , fontsize=9, ncol=1)
265
266     # 3. Energy Generation vs Pump Demand
```

```
    plt.subplot(2, 2, 3)
    plt.plot(range(1, n_days + 1), daily_solar,
             color=COLORS['golden_yellow'], linewidth=1,
                label='Solar Generation')
    plt.plot(range(1, n_days + 1), daily_pump_demand,
             color=COLORS['coral_red'], linewidth=1, label='
                Pump Demand')
    plt.title('Daily Energy Supply vs Pump Demand')
    plt.ylabel('Energy (kWh/day)')
    plt.xlabel('Day of Year')
    plt.grid(True)
    plt.legend(loc='upper center', bbox_to_anchor=(0.5, 0.95)
       , fontsize=9, ncol=1)
    plt.ylim(bottom=0)

    # 4. Energy Surplus/Deficit
    plt.subplot(2, 2, 4)
    daily_surplus = [s - d for s, d in zip(daily_solar,
       daily_pump_demand)]
    plt.plot(range(1, n_days + 1), daily_surplus,
             color=COLORS['lavender'], linewidth=1, label='
                Energy Surplus')
    plt.title('Daily Energy Surplus')
    plt.ylabel('Energy (kWh/day)')
    plt.xlabel('Day of Year')
    plt.grid(True)
    plt.legend(loc='upper center', bbox_to_anchor=(0.5, 0.95)
       , fontsize=9, ncol=1)

    # Adjust ylim if values are very close to zero
    max_surplus = max(daily_surplus) if daily_surplus else 0
    min_surplus = min(daily_surplus) if daily_surplus else 0
    if max_surplus < 1 and min_surplus > -1:
        plt.ylim(min_surplus - 0.5, max_surplus + 0.5)
    else:
        plt.axhline(0, color=COLORS['black'], linewidth=0.5)

    # Finalize layout
    plt.tight_layout(rect=[0.05, 0.05, 0.95, 0.95])
    plt.subplots_adjust(hspace=0.35)

    # Save plot and data
    output_dir = Path('3_hourly_dam_optimization/1_basecase')
    output_dir.mkdir(parents=True, exist_ok=True)

    # Save detailed daily data
    daily_data = pd.DataFrame({
        'Day': range(1, n_days + 1),
        'Storage_Volume': daily_storage,
```

```
        'Water_Pumped': daily_pumped,
        'Irrigation_Need': daily_irrigation,
        'Solar_Generation': daily_solar,
        'Pump_Energy_Demand': daily_pump_demand,
        'Surplus_Energy': daily_surplus
    })

    # Save plot
    plot_file = output_dir / 'optimization_results_solar.png'
    plt.savefig(plot_file, dpi=300, bbox_inches='tight')
    print(f"Plot saved to '{plot_file}'")


    max_storage = max(model.storage_water_level[t].value for
        t in model.time_steps)
    print(f"Max storage level reached: {max_storage:.2f} m
        ")
    print(f"Reservoir capacity: {model.storage_capacity.value
        :.2f} m  ")
    print(f"Difference: {model.storage_capacity.value -
        max_storage:.2f} m  ")

    # Generate readable table
    print("\nOptimal System Capacities and Annualized Costs
        :")
    print
        ("+----------------+----------------+----------------+")

    print("| Component      | Capacity       | Annual Cost ($
        )|")
    print
        ("+----------------+----------------+----------------+")

    print(f"| Reservoir      | {model.storage_capacity.value
        :>8.0f} m      | {dam_annual_val + dam_opex_val:>12,.0
        f} |")
    print(f"| Pump           | {model.pump_power_capacity.
        value:>8.0f} kW    | {pump_annual_val + pump_opex_val
        :>12,.0f} |")
    print(f"| Solar PV       | {model.installed_capacity.value
        :>8.0f} kW    | {solar_annual_val + solar_opex_val
        :>12,.0f} |")
    print
        ("+----------------+----------------+----------------+")

    print(f"| Total          |                | {
        total_annual_cost_val:>12,.0f} |")
    print
        ("+----------------+----------------+----------------+")
```

```
339
340     # Save table values to a text file
341     output_dir = Path('3_hourly_dam_optimization/1_basecase')
342     output_dir.mkdir(parents=True, exist_ok=True)
343
344     table_values = {
345         'Reservoir': {
346             'Capacity': f"{model.storage_capacity.value:.0f}
                    m  ",
347             'Cost': f"${dam_annual_val + dam_opex_val:,.0f}"
348         },
349         'Pump': {
350             'Capacity': f"{model.pump_power_capacity.value:.0
                    f} kW",
351             'Cost': f"${pump_annual_val + pump_opex_val:,.0f
                    }"
352         },
353         'Solar PV': {
354             'Capacity': f"{model.installed_capacity.value:.0f
                    } kW",
355             'Cost': f"${solar_annual_val + solar_opex_val:,.0
                    f}"
356         },
357         'Total': {
358             'Cost': f"${total_annual_cost_val:,.0f}"
359         }
360     }
361
362     # Save to text file
363     with open(output_dir / 'system_capacities_and_costs_solar
            .txt', 'w') as f:
364         f.write("System Capacities and Costs\n")
365         f.write("==========================\n\n")
366         f.write("Component\tCapacity\tAnnual Cost\n")
367         f.write("---------\t--------\t-----------\n")
368         for component, values in table_values.items():
369             if component == 'Total':
370                 f.write(f"{component}\t\t\t{values['Cost']}\n
                        ")
371             else:
372                 f.write(f"{component}\t\t{values['Capacity
                        ']}\t{values['Cost']}\n")
373
374     print(f"\nTable values saved to: {output_dir / '
            system_capacities_and_costs_solar.txt'}")
375
376     plt.show()
377
```

```
378 else:
379     print("\nModel did not find an optimal solution.")
380     print("Check model constraints and parameters for
           potential issues (e.g., infeasibility).")
```

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