

# **Optimized Renewable Energy Powered Irrigation System Using Mathematical Programming: A Case Study for Kiserian, Kenya**

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## Approval

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## Abstract

Energy supply for irrigation in remote areas has been a challenge. Energy is needed to support agricultural activities like pumping water required to enhance crop development and growth in areas that receive less rainfall. There have been efforts to expand the grid for universal access. However, it has been proven to be costly to extend the grid network to remote areas. A suggested solution is to use decentralized systems such as wind and solar. They are affordable, clean sources of energy and readily available. They are affordable, clean sources of energy and readily available. This approach could work well, however, there is insufficiency of data that could help decision makers to settle on the most appropriate solutions. This creates a need for researchers to innovatively develop more data on how solar and wind resources could be optimized for energy applications in agriculture.

This study looked at the optimization of solar photovoltaic and wind turbines to pump water for irrigation as a hybrid system that could be utilized at Kiserian, Kajiado county. Tomato crops were used to determine the energy needed to supply water on a hectare piece of land.

A hybrid energy system of solar PV and wind turbine was designed using an Equilibrium Optimizer (EO) algorithm and simulated using MATLAB R2024b software. The model was used to perform the net present cost of the integrated system to generate the optimal result. Then the levelized cost of energy was determined to assess the economic performance of hybrid system. The results were compared with standalone solar PV and wind turbines.

The study revealed that it was economical for small-scale farmers to power an irrigation system using solar PV as a standalone, and the hybrid of solar PV and wind turbine would work well for large scale farmers.

### **Keywords:**

Renewable energy system, solar photovoltaic, wind turbine, Equilibrium Optimizer Algorithm, Net Present Cost, Levelized Cost of Energy and Optimization.

## **List of Abbreviations**

|          |  |
|----------|--|
| ACO      | Ant Colony Optimization                            |
| ALIN     | Arid Lands Information Network                     |
| AOA      | Archimedes Optimization Algorithm                  |
| ASAL     | Arid and Semi-Arid Land                            |
| CSP      | Concentrated Solar Power                           |
| DE       | Differential Evolution                             |
| DTSP     | Dynamic Travelling Salesman Problem                |
| EO       | Equilibrium Optimizer                              |
| GA       | Genetic Algorithm                                  |
| GDP      | Gross Domestic Product                             |
| GWO      | Grey Wolf Optimizer                                |
| HHO      | Harris Hawks Optimization                          |
| LCOE     | Levelized Cost of Energy                           |
| NPC      | Net Present Cost                                   |
| NPV      | Net Present Value                                  |
| PSO      | Particle Swarm Optimization                        |
| RES      | Renewable Energy System                            |
| SA       | Simulated Annealing                                |
| SMA      | Slime mould Algorithm                              |
| Solar PV | Solar Photovoltaic                                 |
| USAID    | United States Agency for International Development |

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## Definition of Terms

|                                |   |
|--------------------------------|---|
| <b>Metaheuristic Algorithm</b> | Refers to a computational method of solving a complex optimization problem using iteration techniques to obtain an optimal solution (Tsai & Ming-Chao 2023) |
| <b>Renewable Energy System</b> | This is a an energy system from natural resources which do not get depleted from sun, wind, water among others (Nations 2024)                               |
| <b>Optimization</b>            | This is the process of maximizing the value of a system at the lowest cost possible using the limited resources available (Bouaouda & Sayouti 2022).        |

# **Chapter 1: Introduction**

## **1.1 Background of the Study**

Inadequate energy supply limits the growth of agricultural activities. Most of the farming practices in Kenya take place in remote areas, which are far away from the grid. Energy is needed in agriculture because it helps in pumping water required for irrigation in regions that receive low rainfall.

Grid expansion is one of the options, however, it has proved to be costly in marginal areas. It requires proper planning by the government which may take longer to be realized because of the distances involved, sparse population and in some cases uneven terrain. One of the suggested solutions is to use decentralized systems. They are affordable and offer flexibility in terms of acquisition and adoption.

Renewable energy systems such as solar photovoltaic and wind turbines are among the stand-alone systems that are recommended in marginal areas. They are cheaper, green and friendly to the environment. Adoption of such systems can help reduce carbon emissions and promote sustainability.

In applications such as irrigation, where the supply of energy is needed continuously during certain periods for water pumping, the unpredictability nature of RES poses challenges. The proposed solution is to productively use both the energy sources to ensure continuous supply of energy as required. Optimizing a hybrid system that will combine both solar PV and wind turbine using suitable mathematical programming will help resolve the challenges of unreliability and intermittency, especially when required to supply energy for pumping water for irrigation.

## **1.2 Problem Statement**

Energy supply for irrigation in remote areas has been a challenge. Energy is needed to support agricultural activities like pumping water required to enhance crop development and growth in areas that receive less rainfall. There have been efforts to expand the grid for universal access. However, it has been proven to be costly to extend the grid network to remote areas. A suggested solution is to use decentralized systems such as wind and solar. They are affordable, clean sources of energy and readily available. Application of irrigation practices at optimal

levels can help improve production during adverse seasons. However, existing optimization methods have failed to provide optimal solutions to ensure that water is efficiently managed during pumping using renewable energy systems. This study sought to address this gap by developing a more efficient and effective algorithm for irrigation in Kenya. This could help decision makers to settle on the most optimal solutions because the study would more data on optimization of solar and wind resources in different locations. This work proposed to optimize wind and solar energy sources in Kiserian, Kajiado County.

## **1.3 Research Objectives**

### **1.3.1 General Objective**

The general objective of this research was to develop an optimized renewable energy powered irrigation system using mathematical programming, with Kiserian as a case study.

### **1.3.2 Specific Objectives**

- i. To determine the energy requirements for water pumping for irrigation
- ii. To conduct a resource assessment for solar and wind in Kiserian, Kajiado County
- iii. To develop a model consisting of solar and wind energy for an irrigation system.
- iv. To optimize the cost using mathematical programming methods

## **1.4 Research Questions**

- i. What are the energy requirements for water pumping for irrigation in Kiserian?
- ii. How can solar and wind resources be assessed for Kiserian in Kajiado County?
- iii. How can a model of solar and wind be designed for an irrigation system?
- iv. How can an algorithm be used to optimize the cost of the designed system?

## **1.5 Justification**

The findings from this research will directly benefit the small-scale farmers in Kenya by providing an effective use of renewable energy for pumping water required for irrigation. In turn, the yields from agriculture will increase; the operational costs will decline significantly, thus improving livelihoods. Also, the designed system will help the farmer adapt and overcome the challenges of adverse climatic conditions.

The utilization of a hybrid renewable energy will promote environmental sustainability by reducing greenhouse gas emissions associated with traditional diesel-powered systems. The optimized renewable energy system will enhance a greener energy mix.

Economic growth is likely to be stimulated through agricultural productivity. There will also be an improved food security and a tremendous reduction in the poverty index in Kenya. The country is likely to benefit from investors who will be ready to finance these kinds of systems.

### **1.6 Scope**

This study focused on designing a hybrid solar PV – wind and water storage systems in the regions characterized by reception of minimal rainfall. The study evaluated the model performance based on the renewable energy available, the water sources and the general system reliability.

### **1.7 Limitations**

The constraints to the objective functions are site/ location specific, limiting universal applicability of the model.

# Chapter 2: Literature Review

## 2.1 Introduction

This chapter discusses theoretical and empirical concepts related to the topic under study. The theoretical concepts are discussed under the theoretical review section, which is divided into five subsections. The subsections dwell on: Water pumping requirements for irrigation; wind and solar PV systems as energy resources for irrigation; economic feasibility analysis; and optimization techniques. The empirical concepts have been presented in the empirical review sections. Here, past studies have been critically reviewed.

## 2.2 Theoretical Review

### 2.2.1 Technoeconomic Requirement

There are various methods that can be used to assess the economic feasibility of projects. It is not enough that a project is technically viable, a project must also make money. The only way to convince investors to work on a project is by doing economic feasibility of it. This subsection discusses technoeconomic analysis that can be applied in standalone energy applications in agriculture.

### 2.2.2 Levelized Cost of Energy (LCOE)

LCOE is an economic tool that is used to analyze the competitiveness of a given electricity generating technology. It computes the total cost incurred in generating one unit of energy in kilowatt hours (\$/kWh) over the lifetime of the project as discussed by Comello *et al.*, (2017). storage using tools like NPV, levelized cost of energy (LCOE). These methods require a number of inputs. For instance, LCOE you require fixed costs, variable costs, discount rate, time horizon. Time horizon is the economic and it is not based on equipment lifetime because it does economic feasibility for investors for a specified time. It is normally informed by the interest of investors in that project. Limited to the time the investors will get back their money, the timelines.

### 2.2.3 Levelized Cost of Water Pumped (LCWP)

Economic aspects in any investment are important and are always scrutinized at the planning phase. For instance, those generating electricity compute the cost incurred to generate. In literature, Cost of electricity (COE) was studied by (Abid *et al.*, 2022a) and (Boutelli *et al.*, 2022a). This study will focus on the LCWP as discussed by (Nekkache *et al.*, 2024a). This is a financial standard applied to measure the effectiveness of a water supply system for irrigation.

It accounts for all the costal factors involved, including capital, operational and maintenance requirements, energy generation cost and consumption.

This is a key metric to be considered for a system that is stand alone, in that, the energy generated is used to provide power for pumping the needed water. It helps to access the choice of energy source, either wind turbine, solar photovoltaic, or a hybrid of the two and how that translates in terms of cost and environmental sustainability. The management of an irrigation system can rely on this criterion to decide the most appropriate system to meet the demand.

#### **2.2.4 Loss of water supply Probability (LWSP)**

This is a technical benchmark that helps to inform the reliability of the system. For irrigation, there are some regions that experience drought and water supply should be such that it can meet the demand for the crops at any given time. This metric is discussed by (Nekkache *et al.*, 2024a). Most researchers use Loss of Power Supply Probability and Loss of Load Probability (LLP). These two have been used by (Khiareddine *et al.*, 2018) and (Bakelli & Kaabeche, 2019a).

It is presented that high LWSP means the system will have failed to meet the demand for water, which will translate to agricultural production. This criterion is crucial to ensure that the designed system can meet the water requirements of the target crop to assure the farmers of a reliable water supply and guaranteed crop production.

#### **2.2.5 Optimization Methods**

##### **2.2.5.1 Optimization**

Bouaouda & Sayouti (2022) defines optimization problem as an approach for looking for the lowest or highest value of a function of a single or multiple variables of a system that are termed as constraints. This technique tries to exhaust the utilization and value of a system at the minimal expense possible.

Chauhan & Saini (2016) analyzed and revealed that hybrid renewable energy systems present optimization problems that are not linear, non-cambered and with more than one objective that comprises of variables and constraints.

For an optimization to be effectively achieved, Bouaouda & Sayouti (2022) discusses the following points to be considered:

- i. Decision variables – These are the components of a hybrid renewable energy system that needs to be identified and defined. For example, solar PV, wind turbine, battery system, battery inverters etc.

- ii. Objective function – This is where the purpose of optimization is clearly defined, whether it is to lower the cost of the system, to increase reliability, and or to lower the effect it has on the environment.
- iii. Constraints – Refers to the set of attributes factored in the design of the system which may be the size of PV array, wind turbines, batteries, the tilting angle of solar PV, battery efficiency and depth of discharge, the height of the wind turbine and the area of installation of the entire hybrid renewable energy system.
- iv. Optimization techniques – Refers to the methods of sizing the system considering the problems experienced using renewable energy systems; in attempt to developing a better optimized system.

### 2.2.5.2 Optimization algorithms

Previously, several algorithms have been developed and applied. The table below summarizes the algorithms, their strengths and weaknesses:

Table 2. 1: Old algorithms applied

| <b>Algorithm/<br/>Method</b> | <b>Strengths</b>   | <b>Weaknesses</b>  | <b>Source</b>   |
|------------------------------|--|--|---|
| <b>Intuitive methods</b>     | They are easy and simple to implement.<br>They require low mathematical techniques                             | They lack accuracy<br>They have high likelihood of system oversizing or under sizing             | Barrueto Guzmán et al. (2018), Al-Badi et al. (2018), Yahmadi et al. (2019) |
| <b>Analytical methods</b>    | They have higher accuracy compared to intuitive methods<br>They use a set of equations to increase reliability | They still don't offer solutions to high reliability sizing                                      | Kaabeche & Bakelli (2019)   |
| <b>Numerical methods</b>     | They can be used to simulate complex systems<br>They provide an elaborate performance analysis                 | They require a lot of simulation of meteorological data<br>They demand high computational skills | Bouzidi & Campana (2021)  |

Apart from the algorithms mentioned above, there exists metaheuristic algorithms for optimizing renewable energy systems as discussed in the following sections.

### 2.2.5.3 Metaheuristic algorithms

According to the handbook by Tsai & Ming-Chao (2023), metaheuristic algorithm is a computational method where iterations are performed on a given operators to achieve an optimal solution with great acuteness. Thakkar *et al.* (2022) defined metaheuristic algorithm as an algorithm framework of high level that is not dependent on a problem, and that provides guidelines to coming up with an optimization algorithm. Various methods have been developed as discussed below:

**Genetic Algorithm** - MathWorks (2024) terms GAs as the process of solving optimization problems that are both constrained and unconstrained in a manner that the number of individual solutions is repeated in succession until it evolves towards an optimal proposition. They tend to mimic the evolution process of natural selection in efforts to improve the solution of a complex problem in an iterative manner Kanade (2023).

These algorithms are superior. They are able to handle complex problems. However, the downsides of these algorithms require high computing costs. The technique is super sensitive to the choice of parameters, whereby the higher the size of the data, the more complex it is to achieve the solution. They take time to gather a desired solution, sometimes the solution gathers prematurely.

**Differential Evolution** - This method of optimization is also evolutionary and it is used to find solutions to global problems using a sequence of iterations to improve a desired solution Shaji (2021). These algorithms have a high random probability of data distribution, hence offer wider selection space. On the contrary, they require high data for evaluation of a set of functions. Their faster convergence during computation process may not work effectively for global problems. They can only be efficient when applied to a single or a few localized problems.

**Particle Swarm Optimization** - Gad (2022) describes this algorithm as an imitation of flying birds or fish schools, where every solution appears to be like a particle moving at a certain velocity in a space of a problem and the behavior is compared to the neighboring particles. PSO requires a small number of variables to arrive at a solution. However, the pace of convergence is slow, it is vulnerable to very large and complex datasets which may produce poor results.

**Ant Colony Optimization** - This metaheuristic algorithm tends to adopt the trait of some ant species. The ants in this case are the solutions to the problems that are sought by procedures in the format of ants hunting for food using the shortest and most appropriate routes Dorigo &

Stützle (2019). This algorithm is adaptive to problem dynamics, and it is robust in solving problems. The downside of this algorithm is that the system experiences stagnation at some point during the execution process. It may also be considered inaccurate because the computation process converges rapidly.

Simulated Annealing - This technique mimics the slow rate of a cooling metal as atoms cool and lose energy in the lattice until the least possible energy level is reached. Guilmeau *et al.* (2021) discusses SA as mechanism where temperature regulates the search process for an optimal point while keeping the convergence to a global level. SA is efficient and simple to implement, although the rate of convergence is very slow.

#### 2.2.5.4 Meta heuristic algorithms applied in irrigation systems

Improved metaheuristic algorithms have been studied and developed for optimizing renewable energy systems as presented below.

Grey Wolf Optimizer -This optimization method as analyzed by Mirjalili *et al.* (2014) is an inspiration by the social behaviors of grey wolves, their leadership hierarchy, and hunting strategies. They comprise of alpha, beta and omega wolves to run through the search process for the prey, which is the solution, by strategically attacking and seizing the prey. This technique is also iterative in nature, providing updates in the hunting process.

Equilibrium Optimizer - Faramarzi *et al.* (2020) observed the EOs and noted that they are based on physics concepts which propelled the unpredictable balancing of mass in a constrained volume space. During the computation process, the algorithm computes the fitness of each variable, then an equilibrium pool is selected and set as  $C_{pool}$ , with four best solutions ( $C_{eqi}$ ) and the solution's mean as  $C_{eqave}$ . The variables are iterated using the following equation.

$$X_{i+1} = X_i \cdot F + (X_{eq} + GCP \cdot (X_{eq} - rand \cdot X / rand)) \cdot (1F) \quad (5)$$

Where F is an increasing factor; GCP stands for Generation rate Control Parameter.

Archimedes Optimization Algorithm (AOA) - The origin of this algorithm is also on Physics concepts, encouraged by the Archimedes' Principle on objects experiencing pressure from all directions when immersed in a fluid. In this case, Hashim *et al.* (2021) presents this method that, during every iteration, the traits of a particle, that is, its density, volume and acceleration are updated.

Slime Mould Algorithm (SMA) - S. Li *et al.* (2020) discussed SMA on the basis of how a slime mould oscillates in nature. The mechanism is to simulate negative and positive feedback in a wave kind of form, following the slime mould process to achieve an optimal channel.

Harris Hawks Optimization (HHO) - This algorithm represents a hunting nature of hawks where they astoundingly attack and seize the prey. Heidari et al. (2019) analyzes this technique as energy, termed as the 'prey' is reducing following a straight line to achieve an optimal function.

### **2.2.6 Intermittency of the Renewable Energy Sources**

The modelling of the water to be stored in a tank needs to be designed to ensure it meets the water requirements of the plant at any given time. The energy from the hybrid of wind turbine and solar PV need to provide energy that will drive the motor to pump water to the reservoir when the sun and wind are available. The two energy sources may not provide the required energy at some time of the day or night due to their intermittency in nature. Since irrigation in an arid and semi-arid region is preferably done during the mornings and evenings, (Bakelli & Kaabeche, 2019b) proposes two equations that can be used to model the water storage depending on the crop water requirements.

### **2.2.7 Crop Water Demand**

Nekkache et al., (2024a) discusses a model to analyze water demand a given crop. Every crop has a reference evapotranspiration  $ET_o$  and a coefficient  $k_c$ . These two parameters are key at every stage of development and crop type.

### **2.2.8 Irrigation in Kenya**

Embracing irrigation in Kenya will help boost the agricultural sector. Kanda & Lutta (2022) revealed that apart from providing a backbone to the country's economy, agriculture also supplies at least 75% of raw materials to the industrial sector, and almost 60% of exports. Livelihoods of about 80% of Kenyan population is dependent on agriculture (Oguge & Oremo 2018).

Approximately 80% of Kenyan land is arid and semi- arid which is not suitable agricultural activities. AgroSolar (2016) found out that the vast land is unproductive due to water scarcity, because less than 4% of the 5.4 million arable hectares is the only section under irrigation and active agriculture is being practiced.

The report from United Nations Environmental Program, as presented by Hornum & Bolwig, (2020), highlighted the extend of irrigation in the country. They observed that 95% of the products from agriculture are from rain-fed systems, which occupy about 17% of the arable

land in the country. This therefore means that 83% of the land left can only be irrigated to optimally support productive farming. Their report also presented how irrigation has been applied all the way from early 1975 to 2020, as shown below.

#### **2.2.8.1 Irrigation Methods**

The following are various irrigation methods practiced:

##### **i. Surface irrigation**

This method involves movement of water by gravity to the crops. Three types of surface irrigation are practiced, including flood irrigation, border irrigation and furrow irrigation. Flood irrigation involves a mass movement of water that is not controlled by any means. Border irrigation is where water is allowed to flow through a regulated flow area to the targeted farmland. Furrow irrigation is a mechanism that directs water through small channels called furrows constructed within the farming area.

##### **ii. Sub-surface irrigation**

This approach is where water is applied just beneath the soil using trenches constructed or perforated pipes. Here, water is made to stand at the same place throughout the irrigation period, and it seeps through the soil to the crop roots by the process of capillarity.

##### **iii. Sprinkler irrigation**

Water for irrigation is supplied under pressure using a pumping system and it is sprayed to crops using nozzles that are mounted right above the crops, which can be stationary or portable.

##### **iv. Drip irrigation**

This is the most efficient type of irrigation where water is supplied to each plant using emitters. It works in regions with limited water supply and high evapotranspiration. In the country, according to Kanda & Lutta (2022), out of the irrigation methods practiced, drip irrigation is the least at 8%, sprinkler irrigation is at 22% and surface irrigation is at 70%.

#### **Challenges faced by irrigation**

Irrigation system in Kenya is hampered by various challenges as discussed by Kanda & Lutta (2022), especially in the arid and semi-arid (ASAL) areas. Water scarcity is a problem in application of irrigation in Kenya because of adverse climatic conditions in some regions. Water sources are normally affected by drought, some dry up, including underground sources. Water quality, especially from rivers may contain heavy metals, big particle sediments that can cause nozzle clogging, and saline waters that may be unsuitable to some crops. The

affordability of some irrigation infrastructure construction is a problem to most of the small-scale farmers. Some farmers are not able to meet the cost of production and management of an irrigation system.

The irrigation system discussed here is drip irrigation method using an energy source to pump water to the drippers. The reason for this is that drip irrigation is efficient in water usage given that ASAL regions have limited water sources.

Skibko et al. (2022) highlights that in drip irrigation, water application is targeted at the roots of the plant and the greener part is not watered purposely to reduce fungal infection of the crop.

Energy to power the water pumping system can be from wind, solar or a hybrid. Water is pumped through the installed pipes from a water source, which could be a river, a dam, lake, ocean or underground well, to a storage tank or to the drippers directly. Control valves help to regulate the flow of water through the pipes. Pipes are installed beneath the soil and supply water through the emitters at specified intervals.

## **2.3 Empirical Review**

### **2.3.1 Solar photovoltaic system for pumping water**

This system uses solar PV as the only source of energy for water pumping as reviewed by Gevorkov *et al.* (2022), Sharma et al. (2020), Mérida García *et al.* (2020) and Gevorkov & Smidl (2020). Energy from the solar panels is directly connected to the pumping system and the amount of energy available will impact on how efficient the water will be pumped.

Bouaouda & Sayouti (2022) points out that solar PV energy system requires less maintenance costs, and the system does not produce noise to the environment when in operation. However, it suffers problems of energy production fluctuations as weather conditions change.

### **2.3.2 Solar PV-Wind water pumping system**

Li *et al.* (2020), Abid *et al.* (2022) and Boutelli *et al.* (2022) combined solar PV with wind turbines to create a hybrid system that productively used both solar and wind energy. Their main aim was to improve the reliability consistency of power supply as compared to a single source system.

On the lower side, wind turbines require regular maintenance because of the moving parts. Aesthetically, the system does not look attractive (Bouaouda & Sayouti, 2022).

### 2.3.3 Solar PV-Wind-Battery water pumping system

The study in this hybrid system where battery storage has been incorporated into the solar PV-wind hybrid systems has not been extensively conducted. Rehman & Sahin (2016), Li *et al.* (2020) and Abid *et al.* (2022) argued that batteries help to provide a backup storage of excess energy generated during peak production hours when the renewable energy sources are available. This energy stored is then utilized during the intermittent hours.

### 2.3.4 Concentrated Solar Power (CSP) water pumping

Mohammed *et al.* (2021) studied the possibility of using concentrated solar technology together with water storage in an optimal way for sizing a water pumping system.

## 2.4 Research gap

The table below shows a number of algorithms studied in literature with gaps that each present.

Table 2. 2: Strength and Weaknesses of metaheuristic algorithms

| Algorithm                                | Strengths   | Weaknesses   | Sources                         |
|--|---|--|---------------------------------|
| <b>Genetic Algorithms (GA)</b>           | They are robust<br>Handle complex problems well                             | High computing costs<br>Sensitive to parameter choice<br>Slow convergence rate                         | MathWorks (2024), Kanade (2023) |
| <b>Differential Evolution (DE)</b>       | High random probability for data distribution<br>Offer wide selection space | High data requirement<br>May not be effective for global problems<br>Less efficient for large problems | Shaji (2021)                    |
| <b>Particle Swarm Optimization (PSO)</b> | Require fewer variables to find solutions                                   | Slow convergence<br>Poor results on large and complex datasets   | Gad (2022)                      |
| <b>Ant Colony Optimization (ACO)</b>     | Adaptive to problem dynamics<br>Robust in problem solving                   | Rapid convergence may be inaccurate<br>Can experience stagnation                                       | Dorigo & Stützle (2019)         |

|  |  |   |                         |
|--|--|---|-------------------------|
| <b>Simulated Annealing (SA)</b>                | Efficient and straightforward to implement   | Very slow convergence   | Guilmeau et al. (2021)  |
| <b>Grey Wolf Optimizer (GWO)</b>               | Effective in the iteration process<br>Linear convergence helps to expedite the global search | It may be difficult to achieve high level of precision when refining in some cases<br>May not perform well on highly complex problems | Mirjalili et al. (2014) |
| <b>Equilibrium Optimizer (EO)</b>              | A recent and robust algorithm<br>Effective in handling complex computations                  | Information on these algorithms is limited.   | Faramarzi et al. (2020) |
| <b>Archimedes Optimization Algorithm (AOA)</b> | Suitable and effective for technical problems<br>Simple to implement                         | Scope for application is limited<br>It is a new algorithm with less validation  | Hashim et al. (2021)    |
| <b>Slime Mould Algorithm (SMA)</b>             | Very good for complex optimization problems  | Limited validation since it's a new method  | S. Li et al. (2020)     |
| <b>Harris Hawks Optimization (HHO)</b>         | Efficient in discrete and continuous problems<br>Good in exploration                         | May require refining of parameters  | (Heidari et al., 2019)  |

From this summary some algorithms have not been applied, especially the recent ones to optimize irrigation systems.

For instance, EO presents high stability in presenting optimum results at a wide variation of data. It is also efficient and shows the lowest time for convergence Nekkache *et al.* (2024). AOA is also a new metaheuristic algorithm with ability to handle complex optimization

problems and easy to implement. In addition, SMA can operate complex optimization problems. However, all these algorithms have not been applied in irrigation optimization systems.

This study will explore the application of EO algorithm to optimize water pumping system for irrigation.

## 2.5 Conceptual design

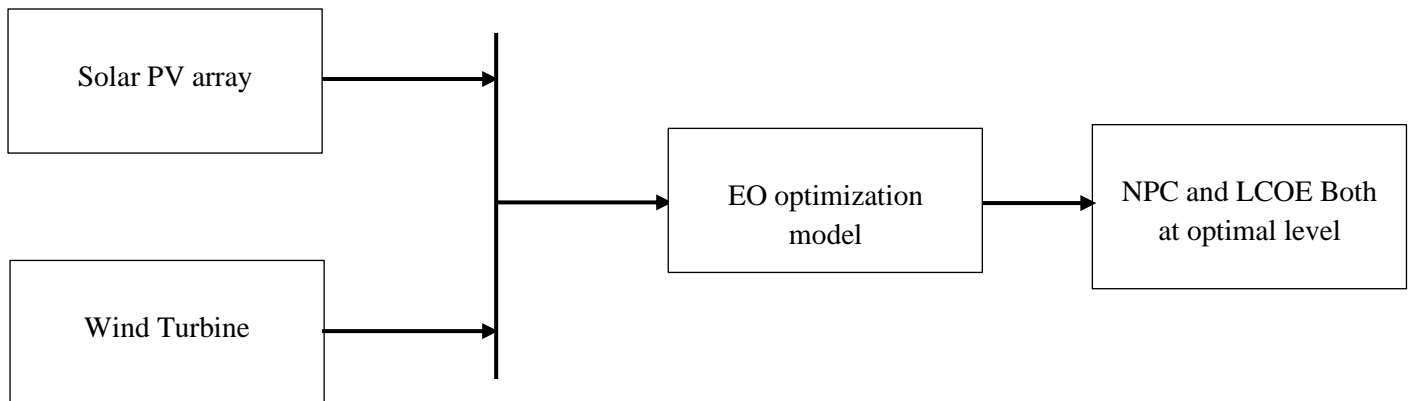


Figure 2. 2: Conceptual model

The optimization process was achieved following the process as shown in figure 2.2. The decision variables that were input into the optimization system were solar PV array and wind turbine. The objective function was to minimize the net present cost (NPC) of solar PV and wind turbines. The constraints will be the number and size of solar PV array and the number and size of wind turbine for a specified power demand. Equilibrium Optimizer algorithm was used to perform the optimization. The optimized NPC was used to determine the levelized cost of energy LCOE.

# **Chapter 3: Methodology**

## **3.1 Introduction**

This chapter presents the outlook of how the research was carried out. It proposed a specific region that was ideal for the setting up of the hybrid system for study. It also outlines how data was gathered and scrutinized. This chapter suggested the preferred software for simulation and how the optimization would be performed. Finally the chapter will discuss how the collected data was analyzed.

## **3.2 Research Design**

This study conducted quantitative research that entailed collection of numerical data on system size, that is the sizes and prices of wind turbines, size and costs of solar panels and other solar PV components including the inverters, cabling among others, crop water, the cost of the water pipes and pumping motors. Reliability and performance metrics such as the time for convergence, standard deviation etc. were performed in the optimization software.

## **3.3 Sampling Criteria**

The population sampling proposed for this study targeted a region that is remote and experiences challenges with water scarcity. The region selected needed to have arable land that could be utilized for agricultural activities when properly irrigated to provide water requirements for the plants.

The type of sampling suggested was purposive sampling that targeted arid and semi-arid regions that had good solar insolation and wind potential to generate energy required for irrigation. In Kenya, according to Monteiro et al. (2010) as discussed in section 2.2, about 80% of the region is arid and semi-arid, and therefore the sampled area for the study could be replicated in other parts of the country with almost similar characteristics. The sampled region is Kiserian town discussed below.

### **3.3.1 Sampled Area**

The proposed study area is Kiserian, Kajiado County. The location is semi-arid and faces significant water scarcity challenges. It is near Nairobi City hence it would offer an advantage especially for data collection and collaboration with research institutions and has also access to infrastructure. The region has good potential for both solar and wind energy which is essential for a hybrid system. Kiserian is a rapidly growing town with increasing population and agricultural activities.

### **3.4 Data Collection**

This study collected data primarily from secondary sources such as Global Solar Atlas, Global Wind Atlas, Climate Data and other desktop sources. The study gathered meteorological data, including historical information on wind speed, solar irradiance, and temperature from local weather stations to evaluate the potential for renewable energy in the region. Additionally, agricultural data about the farming patterns, the type of crops, irrigation practices, water consumptions, and planting seasons was collected from farmers' associations such as Arid Lands Information Network (ALIN) in Kajiado County, hydroponic farmers association in Kajiado County among others. The study also considered information about the local infrastructure and available water sources.

### **3.5 Model and Algorithm Development**

The simulation process will involve defining the problem to be optimized including the objective function. The EO algorithm will be implemented to optimize the configurations for wind and solar components, such as the size and height of wind turbines, and number of solar panels. The following is a flow chart of the optimization process.

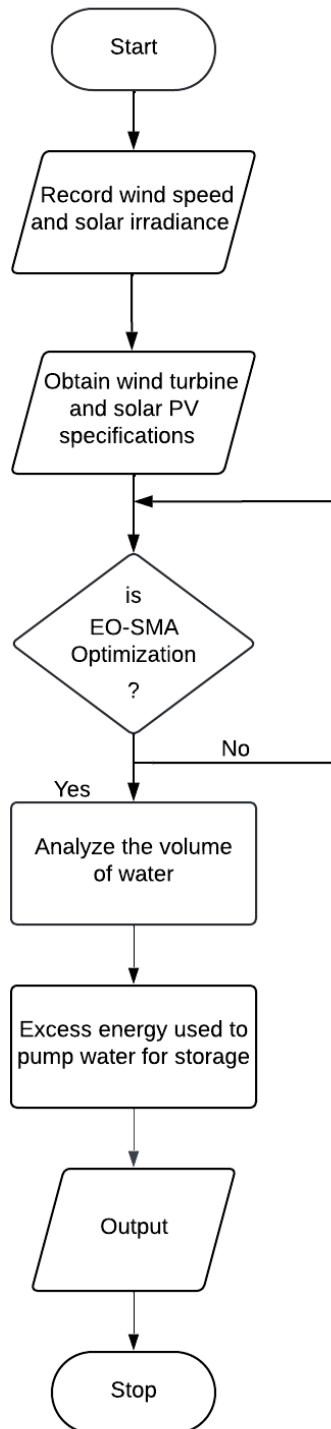


Figure 3. 1: Optimization flow chart

Different dynamics were considered during the simulation process to see how the energy generated from both wind and solar fluctuates and how the system could be designed to avoid under or over generation. The system parameters were refined iteratively to achieve an optimal balance between the energy being produced and the resource utilization.

### 3.6 Simulation Software

There are several simulation software that could be used to develop the hybrid algorithm proposed in this study. However, some present weaknesses that could not work well with this study hence informing the most preferred choice.

Table 3. 1: Simulation Software Summary

| Software        | Strengths   | Weaknesses  |
|-----------------|---|---|
| <b>MATLAB</b>   | Has powerful mathematical capabilities for modelling and simulation   | Could be expensive to acquire<br>Require a steeper learning curve for beginners   |
| <b>Simulink</b> | Contains graphical interface, it has a seamless integration with MATLAB and has a wide range of libraries         | Can be very complex to learn and may not be flexible for certain types of simulations   |
| <b>Python</b>   | Free and open source, versatile in language and large ecosystem of libraries                                      | Requires more manual coding and can be less efficient for certain types of simulations  |
| <b>Modelica</b> | It is a modelling software based on object-oriented language, open source and can model a wide range of languages | Requires a steeper learning curve for beginners, may have limitations for certain optimization problems                         |
| <b>HOMER</b>    | Designed for microgrid modelling, has a wide range of components, user friendly interface                         | It may be less flexible for highly customized simulations; it is limited in its ability to handle complex optimization problems |

Therefore, MATLAB simulation software was adopted for developing EO algorithm for optimizing a hybrid irrigation system. It is capable of computing complex optimization problems. It was customized to achieve the desired algorithm.

### 3.7 Data Analysis

The data collected required a statistical analysis of wind speed; patterns, solar irradiance, air density, atmospheric pressure, temperatures, among others were recorded. Plant analysis of water demands for tomato crops as the target crop, solar irradiance and wind speeds were analyzed to inform the trends and patterns of different seasons throughout the year.

Finally a cost-benefit analysis was assessed to determine the economic viability of the hybrid system in consideration of capital costs, operation costs and energy saving.

### **3.8 Ethical Considerations**

This research was devoted to upholding the highest standards of research ethics. The collected data was handled with a high level of integrity to ensure accuracy and transparency during the entire process.

The MATLAB software proposed for algorithm simulation has been purchased and made available to researchers by the University. In addition to this, the cited work in this study has either been from an open access platform or from the university library portal, in adherence to copyright laws.

Moreover, Strathmore University has provided an Ethical Review Committee, which went through the proposal to safeguard ethical practices. The Ethical certificate provided guidelines that ensured that the study complied with all relevant ethical requirements and guidelines, thus promoting responsible and trustworthy research practices.

# Chapter 4: System Model and Problem Formulation

## 4.1 Introduction

This section presents how the data gathered from secondary sources has been used for Kiserian town, Kajiado County. The energy demand is determined by assessing the crop water requirements and the amount of energy required to pump the water. The chapter discusses how the system model and the objective function have been developed. It also considers the constraints in the problem design and the system reliability of the model. An optimization software was used to optimize the decision variables.

## 4.2 System Modelling and Objective Function

The formulation of the system model considered two decision variables. They include solar PV and wind turbines. A model was designed to determine the optimal sizing for solar PV, wind turbines and the required water storage facility.

### 4.2.1 Case Study Area

Kiserian town is in the Kajiado West region of Kajiado County in Kenya. This area is located at latitude  $-01.430349^\circ$  and longitude  $036.686756^\circ$ . This study proposed to use a five-hectare land from ST Marks Kiserian Mixed Secondary School to implement the project. The parcel of land is 26.3km from Nairobi city.

According to the data collected from Global Solar Atlas, Kiserian receives an annual average Direct Normal Irradiation of  $1532.8\text{kWh/m}^2$ . It also receives an average wind speed of  $5.68\text{m/s}$  and wind power density of  $143\text{W/m}^2$  at a height of 100m from the ground.

### 4.2.2 Energy requirements

The required energy demand was computed by considering the amount of water required to irrigate maize crops per day in a specified piece of land. This helped to inform the type of pump needed for pumping and hence the energy. Therefore, to determine the energy demand for irrigation, fluid power was computed using equation 4.1,

$$P_h = \frac{Q \times \rho \times g \times H}{(3.6 \times 10^6)} \quad (4.1)$$

where:

$P_h$  is the hydraulic power in kW

$Q$  is the flow capacity ( $\text{m}^3/\text{h}$ )

$\rho$  density of fluid ( $1000 \text{ kg/m}^3$ )

$g$  gravitational acceleration (9.81 m/s<sup>2</sup>)

$H$  is the total dynamic head (m)

$Q$  was determined by analyzing the net irrigation water requirements for the tomato crop for a given size of land. The following approach was considered for the study:

Determining the Reference Evapotranspiration ( $ET_o$ )

In this step, obtaining the evapotranspiration potential for maize crop used FAO Penman-Monteith equation as described by (*Chapter 2 - FAO Penman-Monteith Equation*, n.d.).

Penman-Monteith equation for water requirements:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (4.2)$$

where:

$ET_o$  is the reference evapotranspiration [mm day<sup>-1</sup>],

$R_n$  is net radiation at the crop surface [MJ/m<sup>2</sup>/day]

$G$  is soil heat flux density [MJ/m<sup>2</sup>/day]

$T$  mean daily air temperature at 2m height [°C]

$u_2$  wind speed at 2m height [m/s]

$e_s$  saturation vapor pressure [kPa]

$e_a$  actual vapor pressure [kPa]

$e_s - e_a$  saturation vapor pressure deficit [kPa]

$\Delta$  slope vapor pressure curve [kPa/°C]

$\gamma$  psychometric constant [kPa/°C]

The total water requirement ( $ET_a$ ) was obtained using the Equation 4.3,

$$ET_a = ET_o \times Kc \quad (4.3)$$

where,  $Kc$  is the crop coefficient

In order to find the crop coefficient  $Kc$ , the following equation was used as applied by (Djaman et al., 2022).

$$Kc = 0.12 + 0.00168 \times TU - 2.45 \times 10^{-7} \times TU^2 - 4.37 \times 10^{-10} \times TU^3 \quad (4.4)$$

where Kc is the daily crop coefficient, and Tu is a thermal unit in °C

In order to obtain thermal unit (Tu), which is the total growing temperature of the days during the planting season for the tomato crop. It is expressed in Equation 4.5,

$$TU = \sum_{i=1}^n \frac{T_{max} + T_{min}}{2} - T_{base} \quad (4.5)$$

where:

$T_{max}$  and  $T_{min}$  is the maximum and minimum temperature (°C)

$T_{base}$  is the base threshold temperature for tomato crops, and

$n$  is the number of days

Therefore, the net irrigation requirement for tomato crops (NIR) was calculated using Equation 4.6,

$$NIR = ET_a - \frac{\text{Effective rainfall}}{n} \text{ mm/day} \quad (4.6)$$

where  $n$  is the number of days of the growing period for tomato crops.

The effective rainfall was obtained by taking the total rainfall received per year then computed using the USDA-SC approach, as applied by (Bokke & Shoro, 2020).

The discharge capacity Q was calculated using Equation 4.7,

$$Q = \frac{NIR}{\text{Hours of operation}} \quad (4.7)$$

In order to find daily net requirements, the total dynamic head,  $H$  was obtained by combining both the static head and the frictional head i.e.  $H = \text{Static head} + \text{Friction head}$

Darcy Weisbach equation was used to find the friction head as per Equation 4.8,

$$h_f = \frac{fLv^2}{2gD} \quad (4.8)$$

where:  $h_f$  is the friction head,

$f$  is the frictional constant (0.02)

L is the length of the pipe  
 $v^2$  is the velocity of the fluid in m/s  
 $g$  is gravitational acceleration (9.81 m/s<sup>2</sup>)  
D is the diameter of the pipe

Figure 4.1 shows borehole distribution in different locations in Kajiado County.

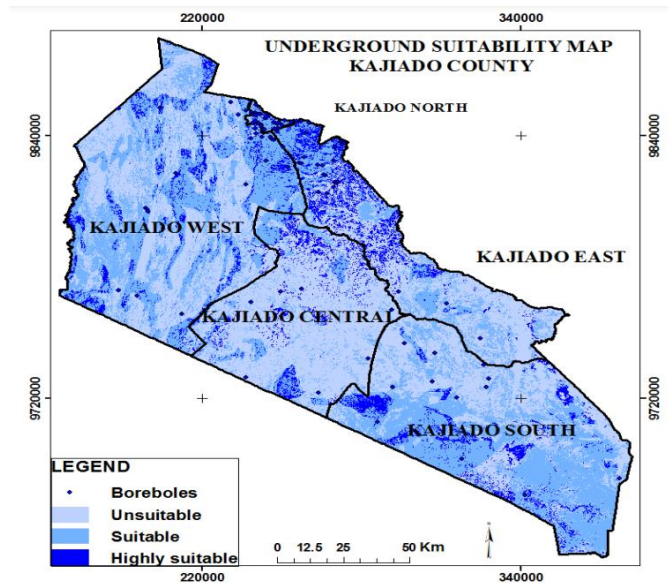


Figure 4. 1: A map distribution of boreholes in Kajiado County

The data on borehole depth, adopted from Ochiba, N.K. (2020) was used to inform the water table in Ongata Rongai, a region next to Kiserian. This aided in determining the pumping head required.

Table 4. 1: Borehole Characteristics in Kajiado County

| B. Serial No.                                   | 6231 | 9292 | 9262 | 13435 | 10663 | 13850 | 13732 | 19870 | 19653 | 20944 |
|---|------|------|------|-------|-------|-------|-------|-------|-------|-------|
| Borehole site                                   | 1    | 2    | 3    | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
| WRL(m)  | 30   | 20.3 | 48   | 51    | 27    | 67    | 43    | 116   | 23    | 50    |
| B. depth  | 210  | 80   | 178  | 234   | 94    | 296   | 162   | 286   | 130   | 160   |
| Yield (m <sup>3</sup> /h)                       | 6    | 12   | 13   | 10.6  | 12.6  | 9.8   | 12    | 10.3  | 10    | 9     |
| Lowest Water Rest Level [WRL] → water table (m) |      |      |      |       | 116   |       |       |       |       |       |

Power required to pump water from the ground is then obtained by taking the hydraulic power of the system and considering the efficiencies during operation as a result of the working of both the motor and the pump, and the load factor was applied.

Therefore, the resultant power equation considered during the study was:

$$P = \frac{P_h \times l_f}{\eta_m \times \eta_p} \quad (4.9)$$

where:

$P_h$  is the hydraulic power

$\eta_m$  is motor efficiency

$\eta_p$  is pump efficiency

$l_f$  load factor (assumed to be 80%)

### 4.2.3 Solar PV Model

The model used to find the solar energy required for the system as applied by Ahmed *et al.*, (2017) is displayed below:

$$P_{pv} = A_m \eta_m I_r \quad (4.10)$$

where:

$A_m$  is the surface area of the PV module (m<sup>2</sup>),

$\eta_m$  is the power conversion efficiency of the PV module

$I_r$  is the solar irradiance

Solar PV output is then calculated by an array of solar PV modules connected in series and parallel as per Equation 4.11,

$$P_{array} = N_s \times N_p \times P_{pv} \quad (4.11)$$

where:  $N_s$  &  $N_p$  are PV modules in series and parallel respectively, and  $P_{pv}$  is the power from PV module.

The following solar PV specifications were taken into consideration:

Table 4. 2: Solar PV Specifications

| No. | Item description     | Specifications |
|-----|----------------------|----------------|
| 1.  | Maximum Power (Pmax) | 550W           |

|     |                               |                |
|-----|-------------------------------|----------------|
| 2.  | Voltage at Pmax (Vmp)         | 40.9V          |
| 3.  | Current at Pmax (Imp)         | 13.45A         |
| 4.  | Short-Circuit Current (Isc)   | 13.45A         |
| 5.  | Open-Circuit Voltage (Voc)    | 49.62V         |
| 6.  | Weight                        | 28.9kg         |
| 7.  | Dimensions                    | 2274x1134x35mm |
| 8.  | Maximum System Voltage        | 1000/1500VDC   |
| 9.  | Overcurrent protection rating | 25A            |
| 10. | Application Class             | A              |
| 11. | Temperature operation         | -40°C - 85°C   |
| 12. | Nominal Op. temp (NOCT)       | 45°C           |

#### 4.2.4 Wind Power Model

Wind power output considers the speed of the wind at a height and the turbine characteristics. The equation adopted in finding the wind power required for the system is given in Equation 4.12,

$$P_{wind} = \frac{1}{2} C_p \rho A V_{wind}^3 \quad (4.12)$$

where:

$C_p$  is the coefficient power of wind turbine

$\rho$  is the air density (kg/m<sup>3</sup>)

$A$  is the area swept by the rotor (m<sup>2</sup>)

$V_{wind}$  is the wind speed (m/s)

The area  $A$  swept by the turbine rotor is obtained by:

$$\text{Swept area} = D \times h \quad (4.13)$$

Where  $D$  is the diameter of the blade and  $h$  is the height of the blade and this height was obtained from the aspect ratio (AR) given by

$$2 = \frac{h}{R}$$

where  $R$  is the radius of the rotor blade.

Figure 4.2 shows a graph of average wind speed for Kiserian, Kajiado County obtained from Global Wind Atlas.

**Mean Wind Speed @Height 100m**

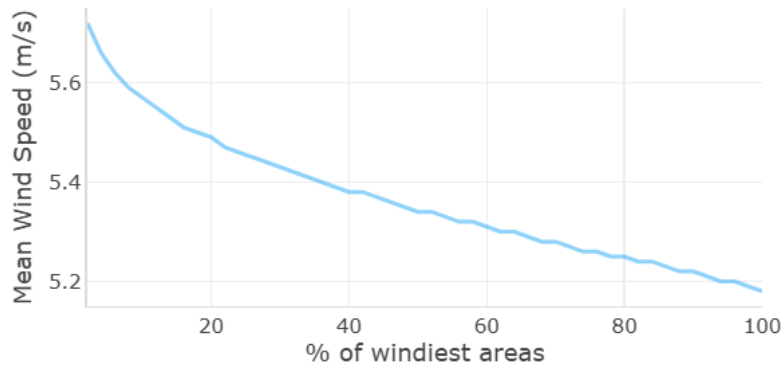


Figure 4. 2: Mean wind speed

Source: Global Wind Atlas (*Global Wind Atlas*, n.d.)

Wind turbine specifications used are presented in Table 4.3 (Ssenyimba et al., 2020)

Table 4. 3: Wind turbine specifications

| No. | Item description    | Value                  |
|-----|---------------------|------------------------|
| 1.  | Start-up wind speed | 2m/s                   |
| 2.  | Wind speed rating   | 9m/s                   |
| 3.  | Blades diameter     | 2.7m                   |
| 4.  | Rated speed         | 400 rpm                |
| 5.  | Size of pipe        | 4.5 inches             |
| 6.  | Blades quantity     | 3-piece blade          |
| 7.  | Blade material      | Reinforced fibre glass |
| 8.  | Rated output power  | 1kW                    |
| 9.  | Stop mechanism      | Electromagnetic brakes |
| 10. | Voltage             | 48V                    |
| 11. | Max output power    | 1500W                  |

The technoeconomic components that were proposed for the system are presented in Table 4.4.

Table 4. 4: Technoeconomic component specifications

| Component        | Specification | Initial cost (\$) | Replacement cost (\$) | O&M cost (\$) | Lifetime (years) |
|------------------|---------------|-------------------|-----------------------|---------------|------------------|
| Solar PV panel   | 550W          | 900               | 900                   | 9             | 25               |
| Wind turbine     | 1kW           | 1000              | 1000                  | 20            | 20               |
| Submersible pump | 1.5kW         | 400               |                       |               |                  |
| Interest rate    | 10.75         |                   |                       |               |                  |
| Inflation rate   | 3.98          |                   |                       |               |                  |
| Project life     | 25 years      |                   |                       |               |                  |

#### 4.2.5 Objective Function Formulation

The main objective of the study was to minimize the Net Present Cost (NPC) of the system. This is presented in Equation 4.14. The minimized NPC was used to determine the least cost of energy (LCOE). The model applied system model constraints.

NPC was determined by combining the initial system cost, the replacement and the maintenance costs of the component system over a lifetime of the project,

$$NPC = C_{init} + \sum_x C_{rep}x + \sum_x C_{main}x \quad (4.14)$$

where:  $C_{init}$  is the initial system cost,  $C_{rep}$  and  $C_{main}$  are the present worth of the replacement and maintenance costs of the system component  $x$ .

The initial system cost was obtained by summing up the cost required to install the entire system, the cost incurred by the solar PV system and that of wind turbines. This is presented in Equation 4.15,

$$C_{init} = C_o + N_{pv}C_{pv} + N_W C_W + C_{pump} \quad (4.15)$$

where:  $C_o$  is the installation cost of the entire system,  $N_{pv}$ ,  $N_W$ , are the numbers of solar PV and wind turbines respectively, and  $C_{pv}$ ,  $C_W$ ,  $C_{pump}$  are the initial costs of solar PV, wind turbines, and submersible pump respectively.

The present worth of the replacement ( $C_{rep}$ ) and maintenance ( $C_{main}$ ) costs are computed using the following equations:

$$\begin{aligned} C_{rep} &= C_{acq} \cdot F^t(1 - F^{tL})/(1 - F^t) \\ C_{main} &= C_{mo} \cdot F(1 - F^L)/(1 - F) \end{aligned} \quad (4.16)$$

where:  $C_{acq}$  is the acquisition cost of component,  $C_{mo}$  is maintenance cost in the first year,  $t$  is the total number of years of which the payment is nonrecurrent,  $L$  is the lifespan of the project, and  $F$  is a factor computed as:

$$F = \frac{(1 + e)}{(1 + i)} \quad (4.17)$$

where:  $e$  is the escalation rate per year and  $i$  is the interest rate.

The cost of one kilowatt per hour of energy, LCOE, was calculated using the following equation as presented by Kharrich *et al.*, (2021):

$$LCOE = \frac{NPC \times CRF}{\sum_{n=1}^{150} P_{load}(t)} \quad (4.18)$$

where:  $n$  is the growing period and  $CRF$  is the Capital Recovery Factor, computed using the following equation:

$$CRF = \frac{i(1 + i)^L}{((1 + i)^L - 1)} \quad (4.19)$$

where  $i$  is the annual interest rate and  $L$  is the project lifetime.

#### 4.2.5.1 System Model Constraints

The system optimization applied specified restraints to keep the search space within solutions. The limits helped in preventing oversizing and under sizing the model. This was applied as discussed by Nekkache *et al.*, (2024b).

The minimum values possible number of solar PV and wind turbines are highlighted as follows:

$$N_{pv, \min} = 0, N_{W, \min} = 0,$$

The maximum possible values, that is the upper limit, were as given below:

$$N_{pv, \max} = 100, N_{W, \max} = 5,$$

where:

$$0 \leq N_{pv} \leq N_{pv}^{max}$$

$$0 \leq N_W \leq N_W^{max}$$

The total energy from both solar PV and wind turbines should be sufficient to meet the demand for irrigation.

$$P_{pv} + P_{wind} \geq P_{load}$$

### 4.3 Optimization of Energy Supply Costs using EO Algorithm

In literature review, it was discussed that Faramarzi *et al.* (2020) proposed the Equilibrium Optimizer algorithm, which relies on the basic principles of physics. When models with a definite mass are bound within a volume space, they adjust themselves until they find an equilibrium balance point, within the space. This phenomena is applied during the optimization process, where the algorithm computes the fitness of each variable, then an equilibrium pool is selected and set as  $C_{pool}$ , with four best solutions ( $C_{eqi}$ ) and the solution's mean as  $C_{eqave}$ . The variables are iterated using the following equation.

Initially when the particle is within a control volume, a first order differential equation is used as shown below to determine the balance position:

$$V \frac{dC}{dt} = QC_{eq} - QC + G \quad (4.20)$$

Where:  $V$  is the control volume,  $C$  is the concentration in the volume space,  $Q$  is the flow rate of the volume into or out of the control volume,  $C_{eq}$  concentration at equilibrium and  $G$  is the mass generation rate in control volume.

When equation 4.1 above, which is an ordinary differential equation is solved, the resultant equation is as shown below:

$$C = C_{eq} + (C_0 - C_{eq})F + \frac{G}{\lambda V}(1 - F) \quad (4.21)$$

Where:  $C_0$  is the control volume concentration at an initial start time  $t_0$ ,  $F$  is the exponential term coefficient and  $\lambda$  is the flow rate.

The exponential term coefficient  $F$  is computed using the following equation:

$$F = \exp(-\lambda(t_1 - t_0)) \quad (4.22)$$

Therefore, as seen above, EO utilizes equation 4.2 to perform the optimization search. The same phenomena is applied when dealing with an optimization problem.  $C$  in this case will denote the solution generated when the current iteration has been performed.  $C_0$  is the value of the previous iteration, and  $C_{eq}$  is the value of the best solution achieved.

When performing an optimization problem, Wei *et al.*, (2022) discusses a general operation approach to be followed as highlighted below:

Initialization – it is performed randomly within the given limits, both minimum and maximum using the equation below:

$$C_i^0 = C_{min} + rand_i(C_{max} - C_{min}), i = 1, 2, \dots, N \quad (4.23)$$

Where:  $C_{min}$  and  $C_{max}$  represents the lower and upper limits respectively, whereas  $rand_i$  is the random number for individual  $i$  of every element in either 0 or 1.

Equilibrium pool – The algorithm performs a set of pools to enhance the search capability and prevent it from falling into local optimum of the equilibrium state of Equation 4.21 above. Normally five possible solutions are selected as presented below:

$$\overrightarrow{C_{eq,pool}} = \{ \overrightarrow{C_{eq,1}}, \overrightarrow{C_{eq,2}}, \overrightarrow{C_{eq,3}}, \overrightarrow{C_{eq,4}}, \overrightarrow{C_{eq,ave}} \} \quad (4.24)$$

Where:  $\overrightarrow{C_{eq,1}}, \overrightarrow{C_{eq,2}}, \overrightarrow{C_{eq,3}}, \overrightarrow{C_{eq,4}}$  represents four best solutions so far and  $\overrightarrow{C_{eq,ave}}$  is the average concentration of the four solutions.

The exponential term factor  $\vec{F}$  adopted for improved searching capabilities of the algorithm is displayed below, as a better version of Equation 4.22.

$$\vec{F} = a_1 \cdot \text{sign}(\vec{r} - 0.5) \cdot (e^{-\vec{\lambda} t_1} - 1) \quad (4.25)$$

$$\text{Where: } t_1 = (1 - t/\text{max}_t)^{(a_2 t/\text{max}_t)}$$

The coefficient  $a_1$  stands for the weight constant coefficient of the global search,  $\text{sign}$  is the sign function,  $\vec{r}$  and  $\vec{\lambda}$  are the random vector numbers of either 0 or 1,  $t$  represents the current number of iterations, and  $\text{max}_t$  is the maximum number of possible iterations.

The generation mass  $\vec{G}$  is an equation used to improve the exploitation potential of the algorithm as displayed by Equation 4.26 below:

$$\vec{G} = \overline{GCP} (\overline{C_{eq}} - \vec{\lambda} \vec{C}) \vec{F} \quad (4.26)$$

$$\overline{GCP} = \begin{cases} 0.5r_1 & r_2 \geq GP \\ 0 & r_2 < GP \end{cases}$$

$\overline{GCP}$  is the vector generation rate of the control parameter,  $r_1$  and  $r_2$  are the random numbers in (0,1) and  $GP$  is the probability of generation.

The final individual solution for the algorithm will be updated as shown in equation 4.27

$$\vec{C} = \overline{C_{eq}} + (\vec{C} - \overline{C_{eq}}) \vec{F} + \frac{\vec{F}}{\vec{\lambda} V} (1 - \vec{F}) \quad (4.27)$$

Where:  $V$  is considered a unit factor of 1.

### EO Algorithm Model for Energy Supply

**Input:** Solar PV data, solar radiation data, wind turbine data, wind speed and system component prices.

### Pseudocode for NPC Optimization using EO Algorithm in MATLAB

1. Initialization of parameters
2. Initialize  $C_o$ ,  $C_{pv}$ ,  $C_w$ ,  $C_{pump}$ ,  $C_{acq}$ ,  $C_{mo}$ ,  $e$ ,  $i$ ,  $t$ ,  $L$ ,  $\text{max}_t$ ;
3. Define  $N_{pv,min}$ ,  $N_{pv,max}$ ,  $N_w,min$ ,  $N_w,max$ ,  $P_{load}$ ;
4. Initialize  $a_1$ ,  $a_2$ ,  $V$ ,  $GP$ ,  $N$ ,  $\text{Dim}$ ;
5. Calculate the factor  $F$  using equation (4.17);
6. Calculate the  $C_{rep}$  and  $C_{main}$  using equation (4.16); //Replacement and Maintenance Costs
7. Calculate the initial system cost  $C_{init}$  by equation (4.15);
8. Calculate the Net Present Cost  $NPC$  by equation (4.14);

9. Apply Constraints

Ensure  $0 \leq N_{pv} \leq N_{pv,max}$

Ensure  $0 \leq N_W \leq N_{W,max}$

Ensure  $(P_{pv} + P_{wind}) \geq P_{load}$

10. Initialize EO Algorithm Parameters

11. Randomly initialize concentration volume  $\vec{C}_i$  for  $i = 1, 2$  to  $N$  within limits using

$$\vec{C}_i = \vec{C}_{min} + \text{rand} * (\vec{C}_{max} - \vec{C}_{min});$$

12. Initialize equilibrium pool  $\overrightarrow{C_{eq,pool}}$ ;

13. EO Optimization Loop

14. While ( $t < max\_t$ )

15. Check boundary constraints and compute fitness  $FitC$ ;

16. Update equilibrium pool  $\overrightarrow{C_{eq,pool}}$ ;

17. Update  $\vec{C}$  and  $FitC$  using greedy strategy;

18. For each search agent

19. Update random variables  $\vec{\lambda}, \vec{r}, r_1, r_2$ ;

20. Randomly select the  $\overrightarrow{C_{eq}}$  in the  $\overrightarrow{C_{eq,pool}}$ ;

21. Calculate  $\vec{F}$  and  $\vec{G}$  using equations (4.25) and (4.26);

22. Update concentrations  $\vec{C}$  using equation (4.27);

23. End For

24.  $t = t + 1$ ;

25. End While

26. Output Optimized Solution

27. Return best solution  $\overrightarrow{C_{eq}}$  and its fitness;

# Chapter 5: Results Analysis and Discussion

## 5.1 Introduction

This chapter presents the results obtained for the power demand and how the load was achieved. This chapter discusses how the sizing of both solar PV and wind turbines was done. Furthermore, the chapter analyses how the techno-economic metrics including net present cost (NPC) and levelized cost of energy (LCOE) were optimally modelled in MATLAB software to achieve a hybrid system of both solar PV and wind Turbine. Finally, a scenario analysis to compare both NPC and LCOE for solar PV alone, wind turbines alone and the hybrid system modelled, for different land sizes.

## 5.2 Energy Demand

The energy required to power the irrigation system was determined by assessing the water requirements of the tomato plant and finding how much power will be required to pump the water from a borehole.

This study used reference evapotranspiration  $ET_o$  and crop coefficient  $K_c$  calculated by CROPWAT software *CropWat*, (n.d.) designed by FAO. It based the calculation using equation (2) (*Chapter 2 - FAO Penman-Monteith Equation*, n.d.).

Considering Equations 4.2, 4.3, 4.4, and 4.5 above for Kiserian, the reference evapotranspiration  $ET_o$  is 4.02mm/day. Crop coefficient  $K_c$  for tomato crops is 1.12, hence the total water requirement  $ET_a$  is 4.5024 mm/day. According to (*Kiserian Climate: Weather Kiserian & Temperature by Month*, n.d.), the average rainfall received annually is 590mm. Therefore, the effective rainfall will be 460.12mm. Tomato crops in semi-arid regions are assumed to take 150 days throughout the growth period. Hence the NIR will be 1.435mm/day per hectare, equivalent to 14.35m<sup>3</sup> per day per hectare, or 14,350 liters/day/ha. The discharge capacity  $Q$  was then found to be 3.6 m<sup>3</sup>/h, assuming a 4-hour operation, where the system pumped water for two hours in the morning and two hours in the evening.

The static head value was taken as 116m after studying the water table presented in table 4.1, whereby from the ten boreholes, the lowest water rest level presents the worst-case scenario.

The frictional head was computed using Equation 4.8. Assuming the internal diameter of the pipe is 75mm, of height 116m long, the friction head was computed and found 0.083m.

The total dynamic head found was 116.083m. The hydraulic power  $P_h$  was found to be 1.14kW.

The actual power was calculated using Equation 4.9, assuming the motor and pump efficiencies as 0.95 and 0.90 respectively, was obtained as 1.1kW. The total load required to irrigate per hectare if the pump is running for four hours per day is 4.4kW.

### **5.3 Solar PV and Wind Turbine Analysis**

According to the data from *Global Solar Atlas*, (n.d.) the Global Horizontal Irradiance is 5.417kWh/m<sup>2</sup>, therefore, assuming a derating factor of 0.75, for a 550W solar panel, the required number of panels is 2 modules.

According to the data obtained from the *Global Wind Atlas*, (n.d.) Kiserian receives wind at a speed of 5.57m/s at a height of 100m and 142W/m<sup>2</sup> mean power density at 10% windiest selected area. The air density adopted for this region is 1.225 kg/m<sup>3</sup>. Betz limit equation was used to compute the power coefficient of value 0.59 as discussed in literature review. Therefore, the actual power produced by the wind turbine is 425W.

### **5.4 Economic Analysis**

Two econometric parameters were used to analyze the performance of the designed model. They included the net present cost (NPC) and the levelized cost of energy (LCOE). The optimized system performed by MATLAB software used solar PV and wind turbines as the decision variables to determine the number of solar PV and wind turbines.

#### **5.4.1 Net Present Cost (NPC) and Levelized Cost of Energy**

The optimized NPC was calculated using equation (4.14) and got \$343740. The value of NPC obtained from the optimization model was used to calculate LCOE using equation (4.18) and found to be 0.061 \$/kWh. Figure 5.1 illustrates a graph of how NPC went through 300 iterations in 30 runs, the value kept reducing at every iteration stage until it converged to a stable state. This was the best NPC achieved after the optimization process.

The result also displayed optimized solar PV panels as 8 and 0 wind turbines. This means that the algorithm analyzed the two energy inputs and decided that for a small piece of land, in this case 1 hectare of land, that required 4.4kW energy, it was only economical to power the system using solar PV system.

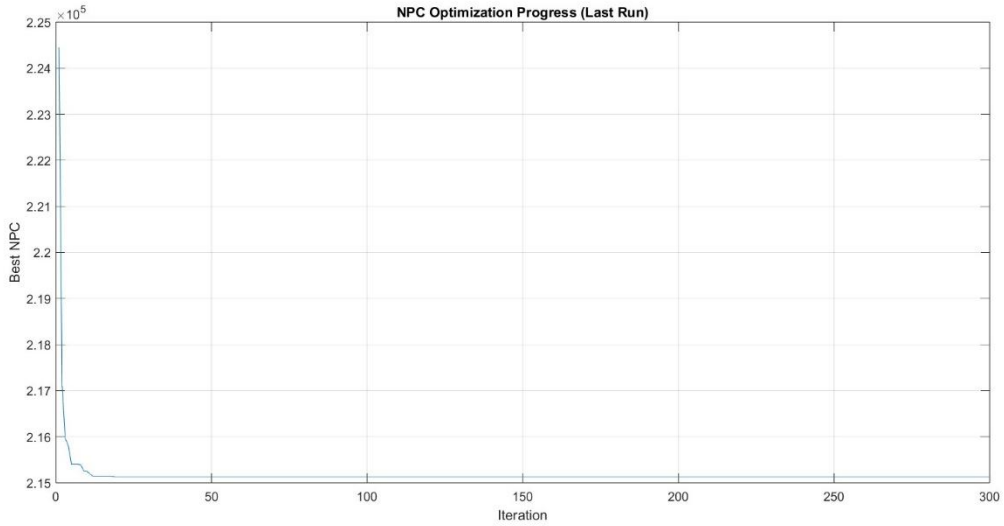


Figure 5. 1 Convergence curve of NPC in Equilibrium Optimizer

#### 5.4.2 Scenario Analysis of the Hybrid System

An equilibrium optimizer algorithm ran ten different optimization scenarios to analyze the performance in different instances. Suppose the model was to provide optimization results for different land sizes, what could be the best numbers for solar PV and wind turbines.. The results achieved were as presented in the graph, figure 5.2:

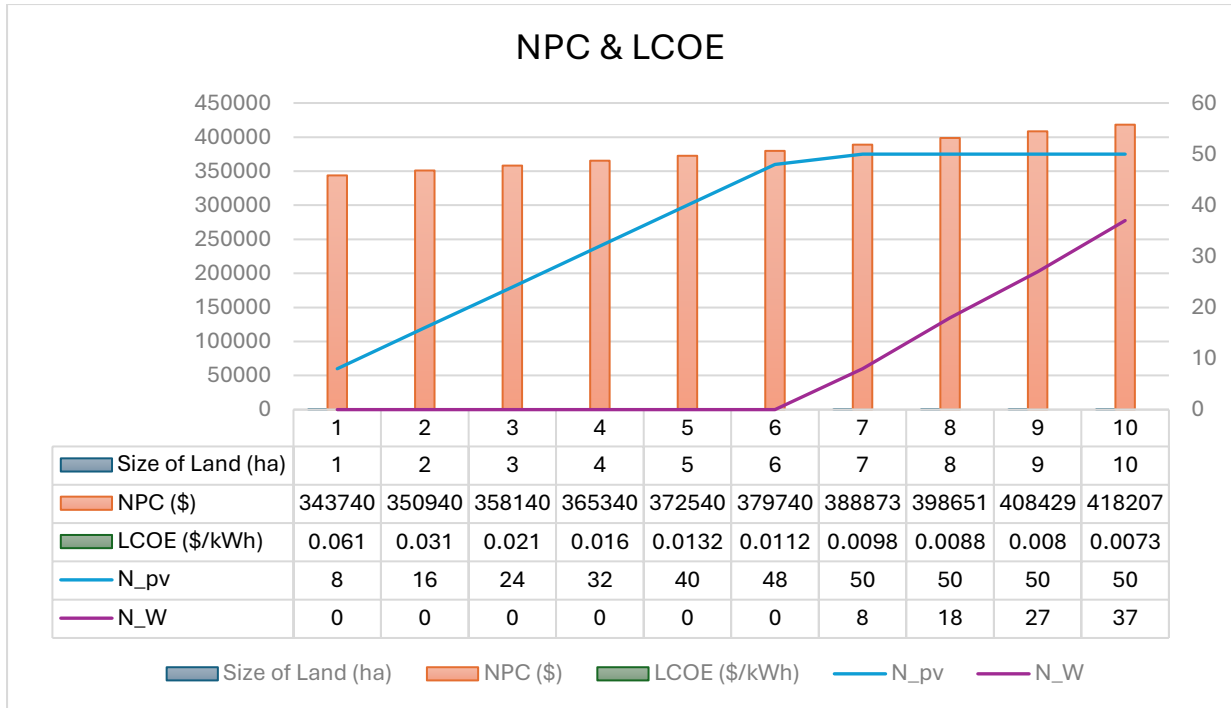


Figure 5. 2: The NPC and LCOE of different land sizes

From the figure 5.2, the value for NPC increased exponentially as the size of the land increased, implying that the system incurred slightly more cost as energy demand increased. LCOE on the other hand reduced proportionately.

The model preferred solar PV for a small system because it was cheaper to power a small farm using a solar PV than wind turbines. The model accepted a hybrid of both wind turbines and solar PV for a land size beyond 6 hectares. This was possible up to 12 hectares beyond which results into an infinite NPV.

### 5.4.3 Comparison of NPC and NPC of the three systems

Microsoft Excel was used to calculate LCOE using the NPV of sole system using Equations 4.14 and 4.18. In the first case if the system was to be powered by solar PV and in the second instance if the system was to be powered by wind turbines. The results for a 1 hectare of land were displayed in the table below compared to the optimized hybrid system.

Table 5. 1: Standalone vs hybrid system

| Energy System     | NPC (\$)      | LCOE (\$) |
|-------------------|---------------|-----------|
| Solar PV          | 9100.07 (NPV) | 0.0624    |
| Wind Turbine      | 2051.68 (NPV) | 0.1324    |
| Hybrid Solar/Wind | 343740        | 0.061     |

Net present value (NPV) was used to determine LCOE in standalone system because if the project was to buy electricity from the utility, how much would have been saved? Therefore, the capacity factor for solar PV was determined by the peak sun hours (PSH) specifically for Kiserian, Kajiado county of 5.417. Hence, the capacity factor was determined if the system was to run for 5.417 hours in a day then the capacity factor will be 22.57%. Electricity would have been bought from the utility at 0.19\$ per unit.

The capacity factor for wind turbines was obtained from the Global Wind Atlas and the value was 13.00%.

The LCOE did not change for either standalone system, even as the size of land increased. On the other hand, the NPV increased.

The findings revealed that it was cheaper for a small-scale irrigation system to be powered by solar PV compared to wind turbines. However, a hybrid system presented a lower LCOE compared to the two standalone systems, implying that a hybrid system would be more economical for large scale farmers with more than 6 hectares of land.

# Chapter 6: Conclusion and Future Work

## 6.1 Introduction

This chapter presents the conclusions drawn from the results of the optimization model. Recommendations are being made on how to design an economical renewable energy system to meet energy demand using Equilibrium Optimizer.

## 6.2 Conclusion

The general objective of the research was to develop an optimized renewable energy powered irrigation using an algorithm. This was achieved through implementation of an optimization model. An optimization model adopted by this study revealed that an optimization technique can be used to address the challenges of intermittency in renewable energy sources. When a hybrid system is integrated, the model is able to predict and carefully simulate the most optimal solution to address the energy need. The optimization algorithm also helped in determining the system parameters to avoid under sizing or oversizing of the energy system.

The most economical way to power a small-scale irrigation (of up to 6 hectares) is to use a standalone solar PV system without energy storage. This is a cost-effective solution in remote areas where there is no grid connection for the small-scale farmers. The system could be designed to irrigate when the sun is available on daily basis and avoid incurring the cost of storing the energy to be utilized when the sun is not there.

A hybrid solar PV and wind turbine will be effective for large scale farmers because it will offer a balance of cost and efficiency. The results also revealed that an integration of solar PV and wind turbines reduced the LCOE by making more energy available during intermittent occasions for either solar PV or wind turbines. The findings highlighted the need for considering both the technical and the economic parameters when designing renewable energy systems to offer solutions in agricultural irrigation.

## 6.3 Recommendations

The implementation of this system is recommended to regions that are semi-arid and that have good wind and solar potential. The performance of the hybrid system depends on the availability of both solar and wind resources because they affect the sizing of the component specifications.

The model is recommended to large scale farmers who could adopt it to meet their energy needs. It is relatively cheaper and efficient compared to individual energy systems.

## **6.4 Future work**

In future studies, research should focus on how to integrate an economical water storage system into the hybrid of solar PV and wind turbine, such that the excess energy generated is not wasted but rather used to pump water to a storage facility. This water could be directed to nearby irrigation area by force of gravity when both wind and solar are low on energy supply.

Research could also be carried out on how to integrate an alternative cheaper renewable energy source with solar PV, instead of wind turbines for small scale farmers. This could help address the intermittency of solar PV when it is just a standalone system.

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# Appendix

## Appendix A: Similarity Report

| Dissertation_Simon_Juma.pdf |  |              |                |
|-----------------------------|--|--------------|----------------|
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## Appendix B: Ethical Clearance Confirmation



21<sup>st</sup> November 2024

Mr Juma Simon,  
simon.juma@strathmore.edu

Dear Mr Juma,

**RE: Optimized Renewable Energy Powered Irrigation System using Improved Hybrid Algorithm. A Case for Kenya**

This is to inform you that SU-ISERC has reviewed and **approved** your above **SU-masters** proposal. Your application reference number is **SU-ISERC2430/24**. The approval period is from **21<sup>st</sup> November 2024 to 20<sup>th</sup> November 2025**.

This approval is subject to compliance with the following requirements:

- i. Only approved documents including (informed consents, study instruments, MTA) will be used.
- ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-ISERC.
- iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-ISERC within 72 hours of notification.
- iv. Any changes anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-ISERC within 72 hours.
- v. Clearance for the export of biological specimens must be obtained from relevant institutions.
- vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.
- vii. Submission of an executive summary report within 90 days of completion of the study to SU-ISERC.

Before commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology, and Innovation (NACOSTI) <https://research-portal.nacosti.go.ke/> and obtain other clearances needed.

Yours sincerely,

A handwritten signature in black ink, appearing to read "Ambrose Rachier".

**Mr Ambrose Rachier,**  
Chairperson; SU-ISERC



## Appendix D: MATLAB Code

%% NPC Optimization using EO Algorithm

```
% This function initialize the first population of particles
function [Cin,domain]=initialization(SearchAgents_no,dim,ub,lb)
Boundary_no= size(ub,2); % numnber of boundaries
% If the boundaries of all variables are equal and user enter a
signle
% number for both ub and lb
if Boundary_no==1
    Cin=rand(SearchAgents_no,dim) .* (ub-lb)+lb;
    domain=ones(1,dim) * (ub-lb);
end
% If each variable has a different lb and ub
if Boundary_no>1
    for i=1:dim
        ub_i=ub(i);
        lb_i=lb(i);
        Cin(:,i)=rand(SearchAgents_no,1) .* (ub_i-lb_i)+lb_i;
    end
    domain=ones(1,dim) .* (ub-lb);
end
end

% Define Problem Parameters
C_o = 500;          % Installation cost
C_pv = 183.5;      % Cost per PV unit
C_W = 700;         % Cost per Wind unit
C_pump = 400;      % Pump cost
C_acq = 883.5;    % Acquisition cost
C_mo = 500;        % Maintenance cost
e = 0.0398;        % Inflation rate
i = 0.105;         % Interest rate
L = 25;            % Project lifespan

N_pv_min = 0;      % Minimum PV units
N_pv_max = 50;     % Maximum PV units
N_W_min = 0;       % Minimum Wind units
N_W_max = 100;     % Maximum Wind units
P_load = 4400;     % Load demand

Run_no=30;         % Number of independent runs
Particles_no=30;   % Number of particles
Max_iteration=300; % Maximum number of iterations
dim = 2;           % Dimensions (N_pv, N_W)
```

```

lb = [N_pv_min, N_W_min];
ub = [N_pv_max, N_W_max];
fobj = @(x) calculate_NPC(x(1), x(2), C_o, C_pv, C_W, C_pump, C_acq,
C_mo, e, i, L, P_load);

% -----
best_npc_runs = zeros(Run_no,1);
for irun=1:Run_no
    Ceq1=zeros(1,dim);    Ceq1_fit=inf;
    Ceq2=zeros(1,dim);    Ceq2_fit=inf;
    Ceq3=zeros(1,dim);    Ceq3_fit=inf;
    Ceq4=zeros(1,dim);    Ceq4_fit=inf;
    [C,domain]=initialization(Particles_no,dim,ub,lb);
    Iter=0; V=1;
    a1=2;
    a2=1;
    GP=0.5;
    best_npc_history = zeros(Max_iteration, 1);

    while Iter<Max_iteration

        for i=1:size(C,1)

            Flag4ub=C(i,:)>ub;
            Flag4lb=C(i,:)<lb;

C(i,:)=(C(i,:).*(~(Flag4ub+Flag4lb)))+ub.*Flag4ub+lb.*Flag4lb;

            fitness(i)=fobj(C(i,:));

            if fitness(i)<Ceq1_fit
                Ceq1_fit=fitness(i);  Ceq1=C(i,:);
            elseif fitness(i)>Ceq1_fit && fitness(i)<Ceq2_fit
                Ceq2_fit=fitness(i);  Ceq2=C(i,:);
            elseif fitness(i)>Ceq1_fit && fitness(i)>Ceq2_fit &&
fitness(i)<Ceq3_fit
                Ceq3_fit=fitness(i);  Ceq3=C(i,:);
            elseif fitness(i)>Ceq1_fit && fitness(i)>Ceq2_fit &&
fitness(i)>Ceq3_fit && fitness(i)<Ceq4_fit
                Ceq4_fit=fitness(i);  Ceq4=C(i,:);

            end
        end

%----- Memory saving-----
    if Iter==0
        fit_old=fitness;  C_old=C;
    end
end

```

```

    for i=1:Particles_no
        if fit_old(i)<fitness(i)
            fitness(i)=fit_old(i); C(i,:)=C_old(i,:);
        end
    end
    C_old=C; fit_old=fitness;
    %-----

    Ceq_ave=(Ceq1+Ceq2+Ceq3+Ceq4)/4;
% averaged candidate
    C_pool=[Ceq1; Ceq2; Ceq3; Ceq4; Ceq_ave];
% Equilibrium pool

    t=(1-Iter/Max_iteration)^(a2*Iter/Max_iteration);
% Eq (9)

    for i=1:Particles_no
        lambda=rand(1,dim); %
lambda in Eq(11)
        r=rand(1,dim); % r
in Eq(11)
        Ceq=C_pool(randi(size(C_pool,1)),:); %
random selection of one candidate from the pool
        F=a1*sign(r-0.5).*(exp(-lambda.*t)-1); %
Eq(11)
        r1=rand(); r2=rand(); % r1
and r2 in Eq(15)
        GCP=0.5*r1*ones(1,dim)*(r2>=GP); %
Eq(15)
        G0=GCP.*(Ceq-lambda.*C(i,:)); %
Eq(14)
        G=G0.*F; %
Eq(13)
        C(i,:)=Ceq+(C(i,:)-Ceq).*F+(G./lambda*V).*(1-F); %
Eq(16)
    end

    Iter=Iter+1;
    best_npc_history(Iter)=min(fitness);
end
best_npc_runs(irun)=min(fitness);
disp(['Run no : ', num2str(irun)]);
disp(['The best solution obtained by EO is : ',
num2str(Ceq1,10)]);
disp(['The best optimal value of the objective funciton found by
EO is : ', num2str(Ceq1_fit,10)]);
fprintf('-----\n');

```

```

end

Ave=mean(best_npc_runs);
Sd=std(best_npc_runs); %main file (main.m):
display(['The average objective function is : ', num2str(Ave,7)]);
display(['The standard deviation is : ', num2str(Sd,7)]);

% Extract N_pv and N_W from the best solution (Ceql)
best_N_pv = Ceql(1);
best_N_W = Ceql(2);

display(['N_pv : ', num2str(best_N_pv,7)]);
display(['N_W : ', num2str(best_N_W,7)]);

% Section 3: Output and Plotting
% Plotting the best NPC over iterations (for the last run)
figure;
plot(1:Max_iteration, best_npc_history);
xlabel('Iteration');
ylabel('Best NPC');
title('NPC Optimization Progress (Last Run)');
grid on;

% Section 4: Fitness Function
% Fitness Function
function npc = calculate_NPC(N_pv, N_W, C_o, C_pv, C_W, C_pump,
C_acq, C_mo, e, i, L, P_load)
P_pv_power = N_pv * 550; % Example PV power (adjust as needed)
P_wind_power = N_W * 450; % Example Wind power (adjust as needed)

F = (1 + e) / (1 + i);
C_rep = C_acq * (F.^(1:L)) .* (1 - F.^(L-(0:L-1))) ./ (1 - F);
% C_rep = C_acq * (F^t) * (1 - F^(t*L)) / (1 - F^t)
C_main = C_mo * F * (1 - F.^(1:L)) ./ (1 - F);
% C_main = C_mo * F * (1 - F^L) / (1 - F)

if (P_pv_power + P_wind_power) < P_load || N_pv < 0 || N_W < 0
    npc = Inf; % Infeasible solution
else
    C_init = C_o + N_pv * C_pv + N_W * C_W + C_pump;
    npc = C_init + sum(C_rep) + sum(C_main);
end
end

```

## Appendix E: CROPWAT Software

| Month          | Min Temp   | Max Temp    | Humidity  | Wind       | Sun        | Rad                    | ETo         |
|----------------|------------|-------------|-----------|------------|------------|------------------------|-------------|
|                | °C         | °C          | %         | km/day     | hours      | MJ/m <sup>2</sup> /day | mm/day      |
| January        | 9.5        | 28.5        | 65        | 130        | 9.2        | 23.2                   | 4.71        |
| February       | 9.8        | 29.4        | 59        | 130        | 8.9        | 23.4                   | 4.96        |
| March          | 10.1       | 30.4        | 62        | 147        | 8.6        | 23.0                   | 5.11        |
| April          | 9.7        | 29.1        | 73        | 112        | 6.7        | 19.3                   | 4.11        |
| May            | 9.2        | 27.6        | 75        | 78         | 6.2        | 17.5                   | 3.51        |
| June           | 8.5        | 25.4        | 74        | 69         | 5.2        | 15.4                   | 3.02        |
| July           | 8.1        | 24.4        | 72        | 69         | 4.5        | 14.7                   | 2.86        |
| August         | 8.3        | 24.9        | 70        | 86         | 4.2        | 15.1                   | 3.07        |
| September      | 9.0        | 27.1        | 63        | 104        | 6.2        | 18.9                   | 3.92        |
| October        | 9.6        | 28.8        | 63        | 138        | 7.0        | 20.3                   | 4.50        |
| November       | 9.3        | 28.1        | 72        | 130        | 6.5        | 19.1                   | 4.06        |
| December       | 9.3        | 28.0        | 71        | 130        | 8.5        | 21.8                   | 4.38        |
| <b>Average</b> | <b>9.2</b> | <b>27.6</b> | <b>68</b> | <b>110</b> | <b>6.8</b> | <b>19.3</b>            | <b>4.02</b> |

It used Penman Monteith to calculate the average radiation and Reference evapotranspiration. The average radiation for Dagoretti Approved (Ngong Weather station) is 19.3 MJ/m<sup>2</sup>/day and the reference evapotranspiration is 4.02 mm/day.

Rainfall water requirements

Station **DAGORETTI-APPROV**

Eff. rain method **USDA S.C. Method**

|                  | <b>Rain</b>  | <b>Eff rain</b> |
|------------------|--------------|-----------------|
|                  | mm           | mm              |
| <b>January</b>   | 38.0         | 35.7            |
| <b>February</b>  | 45.0         | 41.8            |
| <b>March</b>     | 87.0         | 74.9            |
| <b>April</b>     | 223.0        | 143.4           |
| <b>May</b>       | 195.0        | 134.2           |
| <b>June</b>      | 35.0         | 33.0            |
| <b>July</b>      | 15.0         | 14.6            |
| <b>August</b>    | 20.0         | 19.4            |
| <b>September</b> | 20.0         | 19.4            |
| <b>October</b>   | 53.0         | 48.5            |
| <b>November</b>  | 134.0        | 105.3           |
| <b>December</b>  | 113.0        | 92.6            |
| <b>Total</b>     | <b>978.0</b> | <b>762.7</b>    |