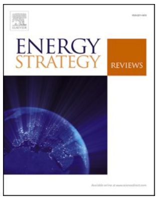
Energy Strategy Reviews 60 (2025) 101806

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr



Using system dynamics modelling to optimize energy and water efficiency of decoupled aquaponic systems: A South African Perspective

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ARTICLE INFO

Handling Editor: Dr. Mark Howells

Keywords:
Energy efficiency modelling
Water efficiency
Sustainable food security system dynamics modelling
Decoupled aquaponics system
Biosystems engineering

ABSTRACT

Despite being energy and water proficient, the practice of aquaponics has remained underdeveloped and underutilized in a poor power generating continent like the African continent and a water scarce society like the Republic of South Africa. As the population of humans on the globe continues to grow geometrically with climate change also being aided, more proficient and safe means of food security premised on energy and water efficiency is becoming the prerogative of governments across different nations. This research has presented a system dynamics model of a decoupled aquaponics system to investigate the sensitivity of parameters in the design of aquaponics systems in the Republic of South Africa. Two major driving variables considered in this research include energy and water utilization for efficient design. A couple of ventilation flow, heating and energy based models were built into the system dynamics model for the conduct of simulation. The results revealed that the top performing countries in respect of energy and water efficiency include locations with hot humid climates such as Brazil, Nigeria and Malaysia. In South Africa, Durban was the best performing city with a peak energy demand of 18.4 MW and a total yearly energy usage of 4550 MW. Durban had a 7.3 % higher cumulative energy compared to Brazil. Durban had a net water return of 124.8 $\times 10^3\ m^3$. Given the humid and hot climate in the city of Durban, it is considered to be competitively suitable for aquaponics operations. Other regions in South Africa could still be suitable to operate aquaponics systems however, this might be less energy and water efficient. The outcome of this research can be utilized by local governing authorities to ensure sustainable policy design and implementation.

Nomenclature

Acronyms	
AHU	Air handling unit
HP	Hydroponic system
HVAC	Heating, Ventilation & Air-Conditioning
RAS	Recirculating aquaculture system
UASB	Up flow anaerobic sludge blanket reactor
Alphabetic symbols	
A_{fHP}	Floor area of hydroponic greenhouse (m^2)
$A_{f,RAS}$	Floor area of RAS facility (m^2)
D_v	Daylight value (Binary)
COP_{chil}	Coefficient of performance of chiller for cooling of RAS facility (−)
COP_{HP}	Coefficient of performance of heat pump for hydroponic greenhouse heating (−)
COP_{heat}	Coefficient of performance of heat pump for cooling of RAS facility (−)
ET	Evapotranspiration rate ($kg_{H2O}.m^{-2}.s^{-1}$)
g	Gravitational acceleration ($m.s^{-2}$)
$H_{HP,cp}$	Pump head for RAS circulation pumps (m)
$H_{HP,pump^+}$	Pump head for HP heating pump (m)
$H_{RAS,chil\ p^-}$	Pump head for RAS HVAC cooling pumps (m)
$H_{RAS,cp}$	Pump head for RAS circulation pumps (m)
$H_{RAS,heat\ p^+}$	Pump head for RAS HVAC heating pumps (m)
H_{RAS,O_2}	Pressure drop for RAS oxygen compressors (Pa)
$\dot{m}_{ex}$	Mass flow rate of make-up water ($kg.s^{-1}$)
$\dot{m}_{w\ evap}$	Mass flow rate of water vapour to RAS environment ($kg.s^{-1}$)
$\dot{m}_{w\ cond}$	Mass flow rate of water condensation on HVAC coils ($kg.s^{-1}$)
$P_{HP,lt}$	Light power rating for hydroponic greenhouse ($W.m^{-2}$)
$P_{RAS,lt}$	Light power rating for RAS facility ($W.m^{-2}$)

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https://doi.org/10.1016/j.esr.2025.101806
Received 31 May 2022; Received in revised form 16 March 2025; Accepted 22 June 2025

(*continued*)

$P_{RAS,UV}$	UV light power rating for RAS facility (W.m^{-2})
$\dot{Q}_{HP,cd}$	Heat transfer due to conduction and convection in the HP (W)
$\dot{Q}_{HP,ET}$	Heat transfer due to plant evapotranspiration in the HP (W)
$\dot{Q}_{HP,HVAC}$	Heat transfer required to cool or heat greenhouse to setpoint (W)
$\dot{Q}_{HP,infil}$	Heat transfer due to air infiltration (W)
$\dot{Q}_{HP,rad}$	Heat transfer due to radiation in the HP (W)
$\dot{Q}_{HP,sr}$	Heat transfer due to solar radiation in the HP (W)
$\dot{Q}_{RAS,ex}$	Heat transfer to the external environment in the RAS (W)
$\dot{Q}_{RAS,HVAC}$	Heat transfer to cool or heat the RAS facility to setpoint (W)
$\dot{Q}_{RAS,in}$	Heat transfer between internal systems in the RAS (W)
$\dot{Q}_{RAS,TL}$	Heat transfer losses from the tanks to the RAS facility (W)
$\dot{Q}_{RAS,vent}$	Heat transfer due to the ventilation system in the RAS (W)
$\dot{V}_{HP,cp}$	Volumetric flow rate for hydroponic greenhouse circulation pump (m^3.s^{-1})
$\dot{V}_{HP,pump^+}$	Volumetric flow rate for hydroponic greenhouse heating pump (m^3.s^{-1})
$\dot{V}_{HP,v}$	Ventilation volumetric flow rate for hydroponic greenhouse (m^3.s^{-1})
$\dot{V}_{RAS,AHU^+}$	Volumetric flow rate for AHU heating fans (m^3.s^{-1})
$\dot{V}_{RAS,AHU^-}$	Volumetric flow rate for AHU cooling fans (m^3.s^{-1})
$\dot{V}_{RAS,chil\ p^-}$	Volumetric flow rate for RAS cooling pumps (m^3.s^{-1})
$\dot{V}_{RAS,CO_2}$	Volumetric flow rate for Carbon Dioxide stripping (m^3.s^{-1})
$\dot{V}_{RAS,cp}$	Volumetric flow rate for RAS circulation pump (m^3.s^{-1})
$\dot{V}_{RAS,heat\ p^+}$	Volumetric flow rate for RAS heating pumps (m^3.s^{-1})
$\dot{V}_{RAS,O_2}$	Volumetric flow rate for RAS Oxygen compressor (m^3.s^{-1})
$\dot{W}_{HP,cool}$	Power required to cool hydroponic greenhouse to setpoint (W)
$\dot{W}_{HP,cp}$	Power required to power circulation pumps for the hydroponic greenhouse (W)
$\dot{W}_{HP,heat\ pump}$	Power required by the heat pump to heat hydroponic greenhouse to setpoint (W)
$\dot{W}_{HP,lt}$	Power required to power lighting in hydroponic greenhouse (W)
$\dot{W}_{HP,pump^+}$	Power required by the pump to heat hydroponic greenhouse to setpoint (W)
$\dot{W}_{HP,v\ heat}$	Power required by the ventilation fans to heat hydroponic greenhouse to setpoint (W)
$\dot{W}_{RAS,AHU^+}$	Power required by RAS heating AHU (W)
$\dot{W}_{RAS,AHU^-}$	Power required by RAS cooling AHU (W)
$\dot{W}_{RAS,chil}$	Power required by RAS Chiller (W)
$\dot{W}_{RAS,chil\ p^-}$	Power required by RAS cooling pumps (W)
$\dot{W}_{RAS,CO_2\ fan}$	Power required to power CO$_2$ degassing fans (W)
$\dot{W}_{RAS,cp}$	Power required to power circulation pumps for the RAS facility (W)
$\dot{W}_{RAS,heat}$	Power required by RAS Heat pump (W)
$\dot{W}_{RAS,heat\ p^+}$	Power required by RAS heating pumps
$\dot{W}_{RAS,lt}$	Power required to power lighting in RAS facility (W)
$\dot{W}_{RAS,O_2}$	Power required to power Oxygen compressors for the RAS facility (W)
$\dot{W}_{RAS,UV}$	Power required for UV disinfection of RAS facility (W)
Greek symbols	
$\Delta P_{HP,fan}$	Pressure drop in HP system, which the fan needs to overcome (Pa)
$\Delta P_{RAS,AHU^+}$	Pressure drop in RAS AHU system (Pa)
$\Delta P_{RAS,AHU^-}$	Pressure drop in RAS AHU system (Pa)
$\Delta P_{RAS,CO_2\ fan}$	Pressure drop in RAS CO$_2$ degassing system (Pa)
$\eta_{HP,cp}$	Hydroponic system circulation pump efficiency (%)
$\eta_{HP,f}$	Hydroponic system ventilation fan efficiency (%)
$\eta_{HP,pump^+}$	Hydroponic system heating pump efficiency (%)
$\eta_{RAS,AHU\ fan^+}$	RAS facility AHU heating fans efficiency (%)
$\eta_{RAS,AHU\ fan^-}$	RAS facility AHU cooling fans efficiency (%)
$\eta_{RAS,chil\ p^-}$	RAS facility HVAC cooling pump efficiency (%)
$\eta_{RAS,CO_2\ fan}$	RAS facility CO$_2$ fans efficiency (%)
$\eta_{RAS,cp}$	RAS facility circulation pump efficiency (%)
$\eta_{RAS,heat\ p^+}$	RAS facility HVAC heating pump efficiency (%)
η_{RAS,O_2}	RAS facility Oxygen compressors efficiency (%)
ρ_w	Density of water (kg.m^{-3})

1. Introduction

Decoupled aquaponic systems design and sensitivity analysis, premised on systems thinking and dynamics, is beginning to gain significant attention in the literature of biosystems engineering and systems modelling [1,2]. Recent research works have investigated and discussed the energy efficiency of aquaponics systems based on regional climate only. This has resulted in different regions across the globe having a speculative idea or absolutely blank without any tangible data or real information about their fitness to invest into aquaponics systems with all its numerous economic and environmental potentials. In the South African context and Africa at large, it has been reported in the literature that aquaponics systems are fairly new. The same situation applies to the Middle East despite the abundance of solar energy in that part of the world. This is evident by an international survey conducted in 2014 where only a single response was received from each of Ghana, Oman and South Africa [3]. A 2016 survey that yielded 44 responses from aquaponics farmers helped shed the light on the status of aquaponics in South Africa. The study classified the aquaponics farming stage in South Africa as an emerging practice [4] despite its numerous gains.

The aim of this research is to investigate and evaluate from a holistic point of view, the level of energy efficiency of the South African geographical location for aquaponics systems design. This was facilitated by developing an integrated network of all systemic variables and parameters premised on the ambient environmental conditions with the use of the system dynamics approach. System dynamics modelling offers a powerful approach to system simulation to capture the complex dynamic interactions within a system [5].

System dynamics modelling have been deployed in diverse complex human enclaves including economics, agriculture, fisheries, food security, electricity, global warming only to mention a few [21–23]. System dynamics modelling is applied to complex biological systems such as aquaponic systems across the world. Aquaponic systems grow both fish and plants on a single system where the fish water fertilizes plants, which in turn helps remove some of nitrogen and other nutrients from the water [6]. Aquaponics is not a novel concept but is underutilized and underdeveloped in numerous countries around the globe. System dynamics modelling approaches can be implemented to properly plan sustainable policies and to ensure success in countries where local challenges may deter from implementing aquaponic systems. It can be used to manage energy usage, reduce waste, maximise yield, drive job creation and food security as well as stimulate sustainable fishing and agriculture effectively and optimally.

The world continues to face widespread food insecurity and achieving food security for all is increasingly complicated [7] including nutrient balancing [24]. There are a variety of factors which contribute to an increase in food security like climate change, increase in population and decline in resources as discussed by FAO [8], Bremmer (2012) and Andersen & Lorch [9] respectively.

Almost 20 % of South African households had inadequate or severe inadequate access to food in 2017 [10]. The majority of households in South African informal settlements were moderately or severely food insecure due to lack of access to food, which was directly related to income [11]. An increase in population is putting an increasing strain on natural resources and a country's ability to feed its people.

Food sovereignty through aquaponics has a great potential to address food and nutrition insecurity in South Africa [12]. If aquaponic systems can be modelled by means of system dynamics some complexities can easily be analysed. Parameters such as yield potential, optimal fish to plant arrangements and energy usage can be simulated to observe how the system is affected. Ultimately these models can be integrated with food security within a country in order to evaluate the advantages and disadvantages of these systems. Using system dynamics modelling as a method to conduct energy and water modelling on decoupled aquaponic systems is not currently found in literature. The model offers an approach that leads to quick comparative results which serves as a decision making tool for designers and policy makers to ensure sustainable systems.

Regarding policy formulation in relation to aquaponics systems design and development, the values of the Climate Compatible Growth Program (CCG) of the UK's Foreign Development and Commonwealth Office (FCDO) with the acronym U4RIA i.e Ubuntu, retrievability, reusability, repeatability, reconstructability, interoperability, and auditability was tactically mapped alongside this energy efficiency paper. Ubuntu in this research was upheld via community economic empowerment through the provision of efficient energy and water utilization scheme for an integrated cropping and animal system. A policy on this environmentally friendly and sustainable mixed controlled scheme can be highly beneficial for the economic empowerment of poor societies and creation of jobs for the unemployed in today's world of exploded population, inflated cost of living, high level of unemployment and an ever growing level of crime. The symbiotically controlled system which harnesses the potentials of the ambient environment speaks to the United Nations sustainable development goals number 7 (affordable and clean energy) and 13 (climate action) respectively. Retrievability in this research was achieved firstly by putting in place, an adequate archiving system of resource materials, data and results with a mission tailored towards easy accessibility. A future policy formulation or enhancement in respect of aquaponics system in developing economies such as the African continent amongst others can easily recall and utilize the findings of this research. Reusability in this research is premised on the ability to adopt barely the same set of modeling variables, parameters and governing conditions for a future research that seek to explore the viability of aquaponics research in other nations of the world. Repeatability herein was facilitated through the adaptability of the same energy efficiency model to new investigations with the change of parameters only. Reconstructability was achieved herein by creating room for modifications and improvement using the same design logic. Interoperability was achieved through systems thinking and systems dynamics integrated modeling. Diverse factors interconnected towards energy efficiency for a sustainable aquaponics system was identified from a holistic point of view and built into an integrated model that functions as a single unit for effective energy policy. Auditability herein is premised on continuous monitoring and accountability of quantitative outputs such as energy utilization and power consumption, CO_2 emissions to the environment and water level losses amongst others.

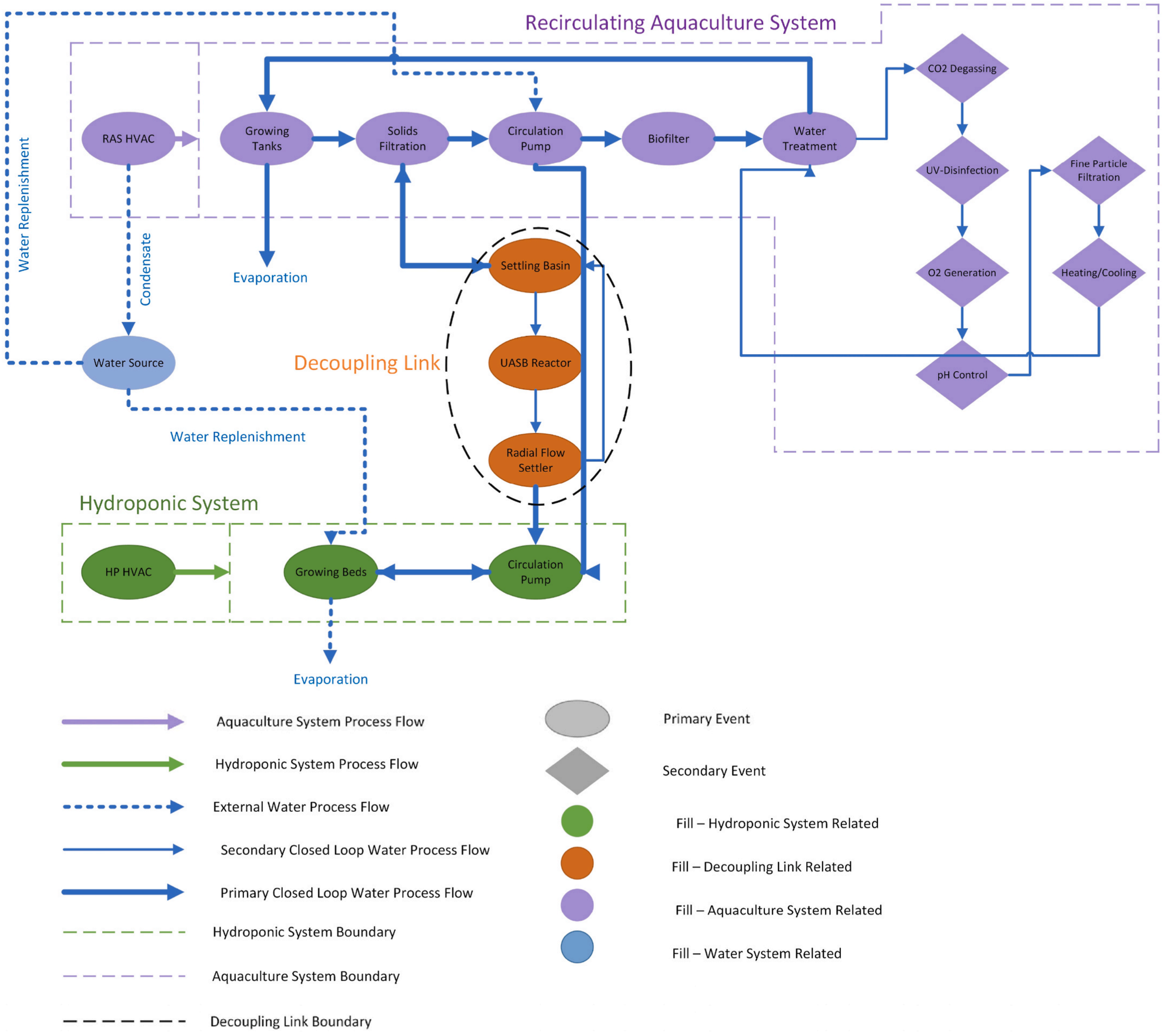

Fig. 1. Decoupled aquaponic system represented in an arrow diagram. The systems are controlled independently via the decoupling link that maintains the mineral, nutrients and independent climate control for the respective system without favouring a single system. Optimal levels for both systems are achieved ensuring maximal yields.

2. Materials and methods

2.1. Notional reference system

As part of the systems thinking methodology, an important step is to identify the system boundaries [5]. A generic notional reference model was based on a decoupled aquaponic system. The system consists of two sub-systems namely a recirculating aquaculture facility and a hydroponic system contained in a greenhouse. The systems are independently adjusted via a nutrient decoupling link to achieve optimal conditions in both systems. The basis of the system steps up was based on the work of Karimanziraa (2016), Goddek et al. [1] and Goddek [2]. Both systems were subjected to environmental control to maintain optimal conditions for fish and crop production. Energy is required to ensure these optimal levels are kept constant. Components required to maintain optimal conditions, which will require power, include lighting, aeration towers, O_2 generation, circulation pumps, UV-disinfection, heating and cooling of water and air and lastly ventilation. Illustrated in Fig. 1 is an arrow diagram representing the system.

In describing the generic model, certain non-varying parameters were defined. These parameters remained constant regardless of the external environment. It was assumed that equipment efficiencies will not change drastically and that construction materials and their properties would not change based on the location. It was assumed that Nile Tilapia was the fish species cultured in the aquaculture facility and that lettuce was the crop grown in the hydroponic greenhouse. The water was maintained at an optimal temperature of 28 °C as used by El-Sayed & Kawanna [13] which observed that Nile Tilapia growth rate is most optimal at this water temperature [25]. The aquaculture facility was maintained at 26 °C to keep the temperature difference between the water and the environment as low as possible whilst still maintaining acceptable comfort conditions for occupants. The greenhouse was maintained at 26 °C ± 2 °C during the day and at 20 °C ± 2 °C during the night. Humidity was not actively controlled in the systems but was maintained via ventilation and dehumidification that occurred during the cooling process. Parameters such as annual production goal, hydraulic retention time and stocking density were based of values from Davison [6]. Ultimately, the system size and site footprint were determined by the annual production goal.

The systems thinking methodology requires a dynamic hypothesis, explaining the cause of the system dynamic elements. It was hypothesised that external factors have a major influence on the system dynamics and how it relates to system energy and water usage. External factors such as air temperature, humidity, pressure, incoming solar radiation, daylight duration and wind speed will have significant impact on the system. Ultimately, certain locations will be more suited from an energy and water efficiency perspective.

2.2. System energy-work balance

Each component in Fig. 1 serves a certain purpose to ensure minimal loss of product and maximal profit. The specific purpose of each component is not discussed in detailed since this is not the primary focus. It is more critical to identify which of these components will require energy input and how the system is affected by surrounding climatic factors.

By applying an energy balance model and considering the 1st law of thermodynamics the system energy and work by the individual components were determined.

2.2.1. Minor energy consumers

Certain components in the system contribute far smaller amounts of energy to the total system energy usage compared the components dedicated to environmental control. Ultimately, these components do not affect the total system energy trend.

Lighting is required to extend the duration of time at which fish could feed and be active. This increases the feed and growth rate ensuring a swift harvest cycle. Lighting was present in the system for 18 h a day [14] and the power requirement is a function of floor area. The energy consumed by the lighting in the aquaculture facility is given as:

$$\dot{W}_{RAS,lt} = D_v A_{f,RAS} P_{RAS,lt} \tag{1}$$

Aeration towers are used to strip the water from CO_2 that is produced by the biomass in the system. Energy is used by the fans to force air over water so that CO_2 can diffuse out of the water into the air stream. The fan power consumption is given as:

$$\dot{W}_{RAS,CO_2\ fan} = \frac{\dot{V}_{RAS,CO_2} \Delta P_{RAS,CO_2\ fan}}{\eta_{RAS,CO_2\ fan}} \tag{2}$$

Circulation pumps maintain the water quality in the system by circulating water through the system and ensuring that system pressure is maintained. The pumps are fitted with variable speed drives to ramp up and down during the life cycle of the fish. The smaller the biomass the less flow is required and therefore energy can be saved. Therefore, the energy is a function of the system biomass. The work by the pump is determined as:

$$\dot{W}_{RAS,cp} = \frac{\rho_w g \dot{V}_{RAS,cp} H_{RAS,cp}}{\eta_{RAS,cp}} \tag{3}$$

The volumetric flow rate is a function of the system biomass and is influenced by fish growth rate, feed rate and feed conversion rates [6]. A piecewise function was used to determine fish growth rate and the feed conversion rates based on fish growth stage and life cycle [15].

Ultra-Violet (UV) lighting is required to remove possible harmful pathogens which can have disastrous mortality effect on an operation. The energy consumed by the UV-lighting in the aquaculture facility is given as:

$$\dot{W}_{RAS,UV} = A_{f\ RAS} P_{RAS,UV} \tag{4}$$

Sufficient dissolved oxygen is required in the water to ensure optimal conditions for fish growth and to limit mortality. Oxygen is introduced via an oxygen cone which diffuses high pressure oxygen into the water. A compressor is required to keep the oxygen at pressure and to ensure it is introduced into the water stream. The work required by the compressor is determined as:

$$\dot{W}_{RAS,O_2} = \frac{\dot{V}_{RAS,O_2} H_{RAS,O_2}}{\eta_{RAS,O_2}} \tag{5}$$

The hydroponic greenhouse was fitted with lighting. Lighting extended the period at which plants can go through growth cycles and biochemical processes. Lighting required energy and released heat into the surroundings:

$$\dot{W}_{HP,lt} = D_v P_{HP,lt} A_{fHP} \tag{6}$$

Under normal operation the greenhouse circulation pumps ran continuously at a constant flow rate. Given the hourly water loss due to evapotranspiration the pump ramped up and down to maintain system pressure. The work by the pump is determined as:

$$\dot{W}_{HP,cp} = \frac{\rho_w g \dot{V}_{HP,cp} H_{HP,cp}}{\eta_{HP,cp}} \tag{7}$$

2.2.2. Major energy consumers

To ensure optimal conditions for fish and crops, the internal environment needs to be controlled and regulated. Creating and maintaining such an environment can be an energy intensive endeavour and it is important to be as efficient as possible. If the system is not closely monitored with regard to energy usage, the running cost could outweigh the profitability of an operation. Heating, ventilation and air-conditioning (HVAC) systems are designed to create optimal environmental conditions by controlling and regulating factors such as temperature, humidity, CO_2 levels and fresh air as required by law. External climatic factors heavily influence the design, operation and efficiency of HVAC systems.

To size equipment, which are identified as power consumers, the system's energy and mass flow were analysed by considering the system as a controlled volume and by applying a mass and energy balance. The energy required to heat or cool the respective systems are given by the following respective equations:

$$\pm\dot{Q}_{RAS,HVAC} = \dot{Q}_{RAS,TL} + \dot{Q}_{RAS,in} \pm \dot{Q}_{RAS,ex} \pm \quad \dot{Q}_{RAS,vent} \tag{8}$$

An approach and assumptions defined by Walker [16], Kindelan [17] and Idso [18] was followed in analysing the energy and mass balance within the greenhouse.

$$\pm\dot{Q}_{HP,HVAC} = \dot{Q}_{HP,sr} - \dot{Q}_{HP,ET} \pm \dot{Q}_{HP,cd} - \dot{Q}_{HP,rad} - \dot{Q}_{HP,infil} \tag{9}$$

A positive term indicates that the systems are cooling to reach set point and a negative term indicates that the systems are heating.

There are three components which consume energy during the cooling and heating of the aquaculture facility, namely the chiller-heat pump, circulation pumps and fans for the air distribution systems. The work required for cooling is determined with:

$$\dot{W}_{RAS,chil} = \frac{+\dot{Q}_{RAS,HVAC}}{COP_{chil}} \tag{10}$$

$$\dot{W}_{RAS,chil\ p^-} = \frac{\rho_w g \dot{V}_{RAS,chil\ p^-} H_{RAS,chil\ p^-}}{\eta_{RAS,chil\ p^-}} \tag{11}$$

$$\dot{W}_{RAS,AHU^-} = \frac{\dot{V}_{RAS,AHU^-} \Delta P_{RAS,AHU^-}}{\eta_{RAS,AHU\ fan^-}} \tag{12}$$

The work required for heating is determined as:

$$\dot{W}_{RAS,heat} = \frac{-\dot{Q}_{RAS,HVAC}}{COP_{heat}} \tag{13}$$

$$\dot{W}_{RAS,heat\ p^+} = \frac{\rho_w g \dot{V}_{RAS,heat\ p^+} H_{RAS,heat\ p^+}}{\eta_{RAS,heat\ p^+}} \tag{14}$$

$$\dot{W}_{RAS,AHU^+} = \frac{\dot{V}_{RAS,AHU^+} \Delta P_{RAS,AHU^+}}{\eta_{RAS,AHU\ fan^+}} \tag{15}$$

Given the high latent heat component, caused by the crops, air-conditioning for purposes of cooling becomes unpractical and expensive. Therefore, the greenhouse was only cooled by means of ventilation and not a cooling coil or evaporative cooling. The work is defined as:

$$\dot{W}_{HP,cool} = \frac{\dot{V}_{HP,v} \Delta P_{HP,fan}}{\eta_{HP,f}} \tag{16}$$

Heating was achieved by means of a heat pump which produces hot water and was used in radiators and via a ducted air handling system. The work of the respective components is defined as:

$$\dot{W}_{HP,heat\ pump} = \frac{-\dot{Q}_{HP,HVAC}}{COP_{HP}} \tag{17}$$

$$\dot{W}_{HP,pump^+} = \frac{\rho_w g \dot{V}_{HP,pump^+} H_{HP,pump^+}}{\eta_{HP,pump^+}} \tag{18}$$

$$\dot{W}_{HP,v\ heat} = \frac{-\dot{V}_{HP,v} \Delta P_{HP,fan}}{\eta_{HP,f}} \tag{19}$$

The total system energy usage for a given time interval is the sum of all energy consuming components as described in Eqs. (1)–(19).

2.3. System water mass balance

Water loss occurred through evapotranspiration in the hydroponic greenhouse system due to the biochemical processes of the crops. Water loss occurred due to evaporation in the aquaculture facility driven by a temperature and humidity gradient within the facility. Water was regained by the condensate water which forms on the cooling coils during the cooling process. Water condensed on the cooling coils when the air temperature is lower than the dew point at the coil condition.

Water that was lost in the hydroponic system and aquaculture systems was replenished from a water storage tank. Water could be replaced directly via the mass balance between the water being lost via evaporation and the water which was regained via the condensation. If the water gained from condensation was less than the water that was being lost, the water needs to be replenished via an external water supply. The external water supply was the measurement of water consumption in the system.

Applying a mass balance to the system yields the following:

$$\dot{m}_{ex} = \dot{m}_{w\ evap} + ET - \dot{m}_{w\ cond} \tag{20}$$

If the balance was negative, there was a surplus of water and the water was stored in the storage tank. The water was then available for future use. The tank water evaporation rate was determined by applying the mass flow analogy of convective heat transfer described by Cengel & Ghajar [19]. The rate of condensation is determined by the dehumidification process governed by the system's psychometric state. The evapotranspiration rate of the crops was determined by methods and theory as discussed by Allen et al. [20].

2.4. Causal loop diagrams

The developed causal loop diagrams are used to describe basic causal mechanisms hypothesised to generate the reference mode of behaviour of the system over time. The reference model, which was simulated over a year, consists of the investigation of the effects of local climatic conditions on system stocks such as energy and water consumption. The causes and effect system variables were used to develop the causal loop diagrams for both the recirculating aquaculture facility (Fig. A.1) and the hydroponic greenhouse (Fig. A.2), respectively. The Causal Loop Diagram (CLD) with about seventy (70) system elements as presented in Figs. A.1 and A.2 in the appendix section, largely expresses sufficiency in respect of the modelling process within the confines of available data and information. The core variables and fundamental system drivers within this problem domain, were largely captured and deployed in the modelling and parameterisation process for both the recirculating aquaculture and hydroponic systems that respectively depicts the aquaponics systems. Reproducibility of the simulation exercise was made easy and feasible through the process of system elements connectivity reconfiguration on the CLD for adaptation to a new and alternative solution.

2.4.1. Balancing loops for the aquaculture facility

The balancing loop, B1 is the relationship between the biomass, fish weight and how they affect the circulation flowrate. The circulation mass flow rate increases as the biomass increases. The biomass is increased when the fish weight and fish feed increase. Fish weight increases since the fish growth rate increases when the feed rate increases. Fish will reach a certain weight where the growth rate will saturate, and the feed rate and the biomass will decrease.

Balancing loop, B2 shows how the aquaculture facility's inside humidity has an effect on the evaporation rate of the tank water. The dynamics of the evaporation rate is a function of the density difference between the vapour mixture at the tank water surface and the environment as well as the mass transfer coefficient. The higher the humidity the more moisture is present in the air. The vapour density has a small gradient, and the evaporation rate will decrease. As the evaporation rate decreases so will the humidity for each hour since the space is being ventilated. The evaporation rate will determine the heat loss to the environment which will contribute to the cooling load. Ultimately, this component will have an influence on the total system energy usage.

The inside humidity is affected by the outside humidity as illustrated by balancing loop B3. If the outside humidity is high, more moisture will be introduced into the system via the ventilation system. The inside water content in the air will then increase. The humidity gradient will therefore increase causing more water to be removed from the air due to dehumidification on the cooling coils. If the condensation rate increases the humidity levels will drop due to dehumidification. The system dynamics are driven by psychometric processes.

The system will consume energy to maintain favourable conditions. Assuming fossil fuels are the main source of electricity generation this will lead to an increase in soot particles due to the burning process. Soot particles can absorb incoming solar radiation preventing the radiation from reaching the surface area of the aquaculture facility. Less solar radiation per square meter will reduce the thermal load on the facility. Balancing loop B4 is particularly of interest for analysing the effects of dependence on fossil fuels for energy generation.

2.4.2. *Reinforcing loops for the aquaculture facility*

Reinforcing loop, R1 illustrates that the burning of fossil fuel will lead to an increase in CO_2 emissions. Over time this can affect a region's temperature due to climate change and global warming. With the increase of the outside air temperature the external system heat will be affected. The temperature difference between inside and outside the RAS is a major contributor to total system energy usage. Delta T is defined as the difference between the inside and outside temperatures. A high delta T will have a significant effect on the total system energy usage, specifically the energy consumed by the HVAC system.

Similarly, the ventilation heat, will be affected since there is a temperature difference in the governing equations as shown by reinforcing loop R2.

Reinforcing loop R3 shows how the set point temperature is controlled by means of the temperature gradient caused by the system heat flux. The system will react to maintain the desired set point by adjusting the current supply temperature of the air.

The last reinforcing loop in the aquaculture facility, R4 indicates that as the set point temperature changes the temperature gradient will be affected and will cause the internal heat and tank heat losses to react.

2.4.3. *Balancing loops for the hydroponic greenhouse*

The internal greenhouse humidity and evapotranspiration rate has a balancing cause-and-effect relationship. When the inside humidity increases the air will become saturated with moisture and the vapour density gradient will become less. The smaller density gradient will cause the evapotranspiration rate to decrease which will in turn decrease the humidity over a period time. The evapotranspiration is influenced by the reference evapotranspiration rate which is a complex term influenced by a variety of factors. Related to the system is outside humidity, which is time varied and will affect the reference evapotranspiration rate. Ultimately, the system is influenced by a latent energy component and the latent energy is driven by the evapotranspiration rate. This relationship is illustrated by balancing loop B1.

If the incoming solar radiation intensity decrease less solar radiation per square meter will reach the greenhouse. This will reduce the thermal load on the greenhouse. This will have an effect on the solar heat gain per square meter but also the evapotranspiration rate, and by extension the heat flux associated with evapotranspiration. The system energy is heavily influenced by the solar radiation since the greenhouse transmits a great deal of solar energy into the system. The reference evapotranspiration rate is also heavily influenced by the incoming solar radiation which has an effect on the latent component of the crop heat balance. The evapotranspiration rate also has an influence on the pump power required. The relationships are described by balancing loops B2 and B3.

2.4.4. *Reinforcing loops for the hydroponic greenhouse*

The effects of CO_2 emissions during the burning of fossil fuels will influence the greenhouse energy balance. With an increase or decreases in external air temperature, heat flux terms with a temperature difference term will be affected. It is hypothesised that the system energy is heavily influenced by external factors such as external temperature. A variety of energy contributing factors are dependent on external temperature. There is a relationship between convective and conductive heat fluxes due to a temperature differential, R4. The heat flux due to infiltration is dependent on the external temperature, R5. Lastly as the outside temperature increase the evapotranspiration rate will also increase, R1. Ultimately, the system energy will be influenced by all these components.

The set point temperature is controlled by means of the temperature gradient caused by the system heat flux. The system will react in order to maintain the desired set point by adjusting the current supply temperature of the air. This cause-effect relationship is illustrated by reinforcing loop R2.

Lastly the ventilation rate will affect the internal humidity, and this will affect the evapotranspiration rate as illustrated by reinforcing loop R3. This will ultimately affect the evapotranspiration heat flux and therefore the system heat flux.

2.5. *System stock and flow*

The dynamic behaviour of the system is simulated using feedback loops. Essentially the feedback loop of the models acts as a path linking decisions, actions, system conditions and information to the path communicating with the decision point.

The most important stock variables identified were as total system energy consumption and total system water consumption. Secondary stock variables such as system humidity, total system biomass, CO_2 levels, O_2 levels and fish weight are also considered and modelled but are less predominant factors. Flows of the system were essentially the per unit time variable namely the heat flux measured in $J.s^{-1}$ and volumetric flow rates measured in $m^3.s^{-1}$. The flows were the rate at which the energy and volume of fluids change over time. Equations representing the system stock were represented by first-order finite difference equations.

The stock and flow diagrams were modelled in the software package known as AnyLogic. To properly illustrate the theory applied during the process of creating the system dynamics model AnyLogic was used. Since, AnyLogic has built in functions specifically used in system dynamics modelling, this software was chosen to construct the stock and flow diagrams. Python was used to handle the large amount of weather data which was fed into the models for all the simulations. Python is suited for this specific model since multiple locations were observed at the same time and advanced mathematical and loop functions were required.

2.6. *Simulation approach*

With the notional reference model defined the simulations could be executed by altering location dependent parameters such as hourly outside air temperature, hourly outside average humidity, site elevation, atmospheric pressure, hourly incoming solar radiation, hourly average wind speeds, hourly daylight intensity and longitudinal and latitudinal site coordinates. These parameters are contained within location specific weather data files based on actual measurements from weather stations. The time parameter was selected in 'days' and the simulations were executed for a single year to compare the climatic effects of different locations with each other. The operation was analysed for a yearly period of 365 days a year. During a yearly period, fish can be harvested three times since the fish have a growth cycle of 120 days. After 120 days the system is purged, cleaned and new fingerlings are added. The greenhouse produces lettuce and has an assumed growth cycle of 100 days. The greenhouse therefore produces three harvests a year and energy is required to sustain half a harvest cycle, which will be harvested the following year. It is important to mention the primary stock flow variables which were identified. The so-called primary stock variables namely, total system energy usage and total system water usage, are two important variables which provides a meaningful indication of how location specific climatic conditions affect a pre-defined generic aquaponic system.

This research aimed to determine whether South Africa would be a suitable location to operate and maintain economically thriving commercial aquaponic systems. Therefore, the simulation results based on the climatic factors of South Africa were compared with a variety of locations selected around the world. International locations were identified based on where current systems, such as cage aquaculture systems, are being operated. There are several locations around the world where fish are being grown on commercial scale. These locations are obviously suitable for operations in terms of the climate and environment. These locations served as an appropriate reference to evaluate how well a similar system will perform from an energy and water consumption point of view. Given the large sample of locations a first round of simulations was conducted to identify the best performing countries in each continent in order to reduce the locations which will be presented.

South Africa has a diverse climate and ranges from humid coastal regions to semi-arid regions. It was therefore important to compare a variety of locations within South Africa to determine where the most suitable location could be. Major cities and economically developed urban areas were considered, given that these locations will be most suitable from an economical, logistical and infrastructural point of view. The locations were further categorised into coastal regions and inland regions for the ease of comparison.

Each global location was categorised based on continent. Each continent could have a variety of countries where aquaculture and hydroponics are being implemented. The two best performing countries on each continent were identified and eventually these best performing locations could be compared on a global scale. Australia/Oceania were excluded due to the stringent policies regarding invasive species. Antarctica was excluded due to extreme undesirable conditions.

Certain locations are situated in the Northern Hemisphere while others are situated in the Southern Hemisphere. To ensure comparability between these locations, with regard to seasonal trends, the model considered and simulated a seasonal year rather than a standard calendar year, i.e., at the start of Summer to the end of Spring rather than 1 January to 31 December.

Locations where aquaculture and aquaponics are implemented currently, experience conditions which are often so favourable there is no need for water recirculation or growing facilities as proposed by this research. Asian countries for example make use of outside cage farming since there is an abundance of water and the climate is very mild. This type of operations requires a minimal amount of resources and energy and therefore more profit can be made. To ensure comparability the generic system was constructed. The generic system was defined by a fixed set of parameters, such as facility size, yield goals, physical system components configuration, water quality and construction materials. Therefore, solely the effects of local climatic factors on aspects such as energy and water usage, was evaluated based on a constant input system. Data smoothing techniques were applied to better visualise the results. A list of the locations used in the simulations are summarised in Tables 1 and 2.

It must be mentioned also that the average annual atmospheric pressure was largely a function of a geographic variable such as the weather station. The weather station very often, is location dependent and measured by height above the sea level. This makes the average annual atmospheric pressure and a few other variables measurable quantities due to the nonlinearized quantitative attribute.

Table 1
List of South African location that were part of the comparative simulation models. Climate classification and weather station coordinates are provided.

Domestic locations		
Location	Weather station coordinates	Climate classification
Cape Town	33.97 S, 18.60 E	Mediterranean climate
Durban	29.62 S, 31.13 E	Humid subtropical climate
Johannesburg	26.15 S, 28.00 E	Oceanic subtropical highland climate
Kimberley	28.80 S, 24.77 E	Hot semi-arid climate
Mokopane	24.2 S, 29.00 E	Hot semi-arid climate
Nelspruit	25.43 S, 30.98 E	Subtropical highland climate
Port Elizabeth	33.99 S, 25.62 E	Humid subtropical climate
Pretoria	25.92 S, 28.22 E	Humid subtropical climate (Monsoon)
Welkom	28.0 S, 26.67 E	Cold semi-arid climate

Table 2
List of Inter-continental location that were part of the comparative simulation models. Climate classification and weather station coordinates are provided.

International locations		
Location	Weather station coordinates	Climate classification
Egypt	**30.783 N, 31.0 E**	**Tropical and subtropical desert climate**
Nigeria	**9.25 N, 7.0 E**	**Tropical savanna climate**
Uganda	**0.68 N, 34.17 E**	**Tropical rainforest climate**
Zambia	**15.33 S, 28.45 E**	**Humid subtropical climate**
Bangladesh	24.25 N, 89.93 E	Tropical savanna
China	23.17 N, 113.33 E	Humid subtropical climate
Indonesia	5.524 N, 95.42 E	Tropical rainforest
Laos	17.99 N, 102.56 E	Tropical savanna climate
Malaysia	6.2 N, 100.4 E	Tropical monsoon climate
Myanmar	25.367 N, 97.4 E	Humid subtropical climate
Philippines	17.555 N, 120.36 E	Tropical savanna
Taiwan	25.07 N, 121.55 E	Humid subtropical climate
Thailand	16.333 N, 100.37 E	Tropical savanna
Vietnam	10.083 N, 105.72 E	Tropical savanna
Germany	52.47 N, 13.4 E	Marine west coast climate
Netherlands	53.13 N, 6.58 E	Marine west coast climate
Portugal	38.73 N, 9.15 W	Subtropical-Mediterranean climate
Spain	40.45 N, 3.55 W	Semi-arid climate
United-Kingdoms	55.867 N, 4.267 W	Marine west coast climate
Germany	52.47 N, 13.4 E	Marine west coast climate
USA (AZ)	33.45 N, 112.0 W	Tropical and subtropical desert climate
USA (CA)	37.62 N, 122.4 W	Mediterranean climate
USA (FL)	28.55 N, 81.33 W	Humid subtropical climate
USA (IA)	42.05 N, 93.85 W	Marine west coast climate
USA (IL)	41.78 N, 87.75 W	Hot-summer humid continental climate
USA (NY)	40.78 N, 73.97 W	Humid subtropical climate
USA (OH)	40.0 N, 82.88 W	Hot-summer humid continental climate
USA (TN)	35.6 N, 88.92 W	Humid subtropical climate
USA (TX)	31.58 N, 94.72 W	Humid subtropical climate
USA (VT)	44.2 N, 72.6 W	Mediterranean climate
Brazil	8.61 S, 38.59 W	Tropical wet
Colombia	2.95 N, 75.29 W	Tropical climate
Costa Rica	10.15 N, 85.45 W	Tropical wet
Ecuador	2.21 S, 81.0 W	Hot semi-arid climate
Honduras	15.72 N, 87.48 W	Tropical rainforest climate

3. Results and discussion

3.1. Location independent energy time response

Certain components are process driven rather than influenced by the external environment. These components included the aquaculture circulation pumps, O_2 generation, CO_2 degassing, aquaculture lighting and UV-disinfection. The system biomass drives the energy usage of these components and since a constant internal environment was maintained throughout the year for each location the energy time series was the same.

UV-disinfection was required at a constant rate since the operation was continuous. Lighting was subjected to a constant hourly schedule and therefore the hourly sum of each day was constant throughout the year. Lighting consumed energy at $9x10^{-3}$ $MW.day^{-1}$ and the UV-disinfection consumed $3x10^{-3}$ $MW.day^{-1}$ for 365 days of the year.

Under the favourable conditions, which were maintained throughout the year, the fish had an exponential growth rate which also influenced the feed rate and excretions. These factors caused the total system biomass to increase exponentially until harvest. With the exponential increase in system biomass, biological processes such as CO_2 generation and O_2 consumption followed the same trend. With a constant hydraulic retention time the system required an increased system flow to ensure proper water quality. With the exponential increase in CO_2 generation, O_2 consumption and system flowrate the energy associated with CO_2 stripping, O_2 replenishment and increased flowrate also followed an exponential increase in energy usage throughout the harvest cycle. The energy increased exponentially until the fish were harvested and the system was purged. Since the fish were harvested three times a year the energy usage followed a cyclic exponential time response throughout the year. The peak energy usage occurred just before harvest, at the point where the system biomass was the greatest. The highest energy consumers were the circulation pumps with a peak demand of $75x10^{-3}$ $MW.day^{-1}$. The O_2 generators required $15x10^{-3}$ $MW.day^{-1}$ at peak demand and the CO_2 degassing required $2x10^{-3}$ $MW.day^{-1}$. The CO_2 degassing was the least energy intensive consumer in the system.

All location independent energy consumers, shown in Fig. 2, had minimal contribution to the total system energy usage and did not significantly influence the trend.

3.2. Location dependent energy time response

The remaining energy consuming components were heavily affected by external conditions and are therefore location dependent. The remaining components included lighting required for the hydroponic greenhouse, hydroponic circulation pumps and HVAC for both systems.

The lighting schedule was subjected to an hourly schedule and the daylight available for a certain season and region. The circulation pump's flow rate is a function of the evapotranspiration rate of the crop and therefore varied based on the external conditions. Only the top performing region of each selected continent is presented in Fig. 3.

Generally, most regions had a similar trend with regard to the circulation pump energy usage. During summer seasons a higher circulation demand was experienced due to water loss via evapotranspiration. During colder winter seasons the temperature differential was less, and less water was lost via evapotranspiration. It was noted that hot humid regions showed a more uniform trend throughout the year compared to countries where the seasons differ drastically. The system imitated an undampened system response for a yearly period and without drastic change in temperature the system should follow the same trend annually. Countries close to the equator will experience similar daylight conditions throughout the year whereas countries located further away will experience more extreme variations in daylight duration in summer and winter seasons. It was evident that daylight is heavily influenced by location and therefore the requirement for supplementation of artificial light during certain times of the year.

The major contributors to the total system energy usage were the HVAC systems serving the HP system and RAS facility. The energy demand was in the order of magnitude 10^6 Watts. The top performing region in each continent is presented in Fig. 4. The various energy components and indicators are indicated in Table 3.

The results revealed that environmental control is the most energy intensive component of the defined aquaponic system. Between 98 % and 99 % of the total system energy is used to maintain favourable internal conditions, for year-round operation. The environmental control is heavily affected by external weather conditions, since the external air temperature, humidity and incoming

solar radiation of a region determines how much energy is required to heat or cool the aquaponic system to maintain favourable conditions. The results revealed that ultimately the dominant energy contributor (heating or cooling demands) will determine the overall system response.

It was observed that regions which experience cold weather, such as North America, Europe and parts of South Africa, had significantly higher energy demands throughout the year due to heating requirements. Energy required for heating outweighed the energy required for cooling for these regions. Cold regions required 20 %, or more, energy throughout the year compared to the best performing region. These cold regions often experienced temperatures below zero. This caused rapid heat loss due to the high temperature differential which led to high energy demands.

The results revealed that regions which experienced high temperatures and high humidity for prolonged periods of time throughout the

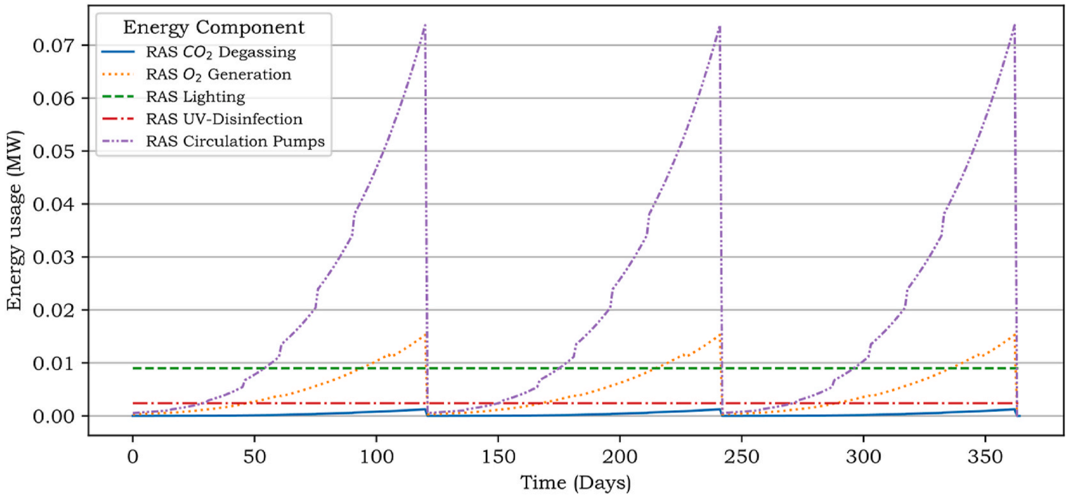

Fig. 2. Simulation results for energy consuming components of the aquaponic system that are independent of location and that are process driven. Simulations were for continuous operation for an entire year.

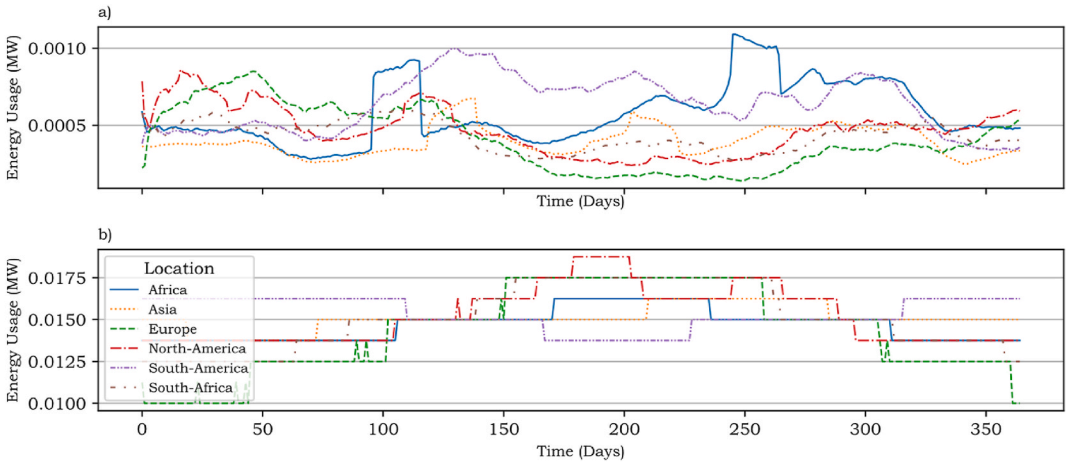

Fig. 3. Simulation results for energy consumed by the hydroponic circulation pump (a) and the artificial lighting in the greenhouse (b). These components are minor contributors to energy usage but are location dependent and are influenced by external factors. Simulations were for continuous operation for an entire year.

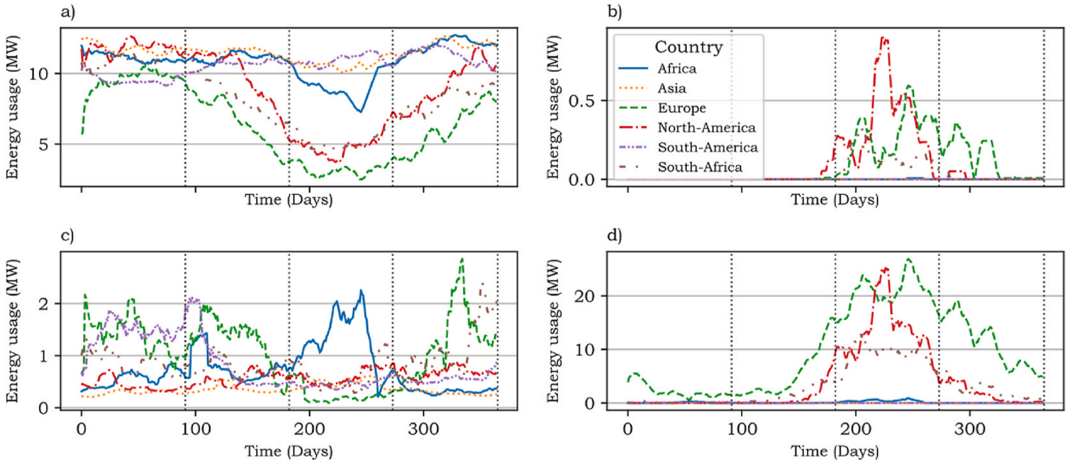

Fig. 4. Simulation results for energy required to (a) cool and (b) heat the RAS facility, and to (c) cool and (d) heat the hydroponic greenhouse to the simulated setpoint. These are the major contributors to energy usage and are influenced by external factors. Simulations were for continuous operation for an entire year.

year had the best energy performance. Countries close to the equator such as Malaysia, Brazil and Nigeria had little difference in temperature and humidity experienced throughout the year. The constant high temperatures and humidity caused more uniform energy demand profiles thought out the year. Minimal heating was required for these regions and cooling was the dominant energy contributor. It can be concluded that regions that experience tropical climates are the most suited for aquaponic systems with regard to energy usage. Durban is the most tropical region that was considered for local comparison; hence this conclusion is confirmed by the fact that Durban was the best performing region in South Africa.

3.3. Total system energy usage

It was observed that the major contributors to the total system energy usage were RAS cooling and HP heating. Other components had minor influence on the system response and the RAS cooling, and HP heating components ultimately determined the final energy demand trend. The simulations revealed the top performing regions with regard to total system energy usage (Fig. 5). The system response is plotted together with the cumulative energy usage for each region. The results are summarised in Table 4.

The results revealed that Brazil, South America was the most energy efficient country to operate a system as described in the research, followed by Abuja Nigeria in Africa and Alor Setar Malaysia in Asia. The top three energy performing locations have hot humid climates where minimal heating was required. Cooling demands were the dominant contributor to total system energy usage.

The low performing locations such as Orlando Florida USA and Lisbon Portugal had respective higher energy consumption of 23.6 % and 50.3 %, compared to the top performing country. Although these locations have humid and hotter climates, the duration at which these conditions were experienced were not long enough for energy efficiency. Cold winters caused high heating demands, which were very energy intensive, as seen by the result.

Durban South Africa had a 7.3 % higher cumulative energy compared to the best performing region. Even though the energy usage was higher throughout the year it was still a good performing region. The cooling demands during the summer was comparable with the top three performing countries, and closely followed the same trend and slope as the countries which were more energy efficient. There was a short period of three months during winter where energy demands

Table 3
Summary of the energy contribution of each environmental control component for the respective location's subsystems.

Region	Energy Component	Peak Energy Usage (MW)	Season Variation (MW)	Percentage Contribution to Total Energy (%)
Brazil	RAS HVAC Cooling Total	12.0	2.8	91.3
	RAS HVAC Heating Total	0.0	0.0	0.0
	HP HVAC Heating Total	0.2	0.2	0.3
	HP HVAC Cooling Total	2.0	1.7	7.1
Nigeria	RAS HVAC Cooling Total	12.6	5.1	91.5
	RAS HVAC Heating Total	0.01	0.01	0.0
	HP HVAC Heating Total	0.8	0.8	0.9
	HP HVAC Cooling Total	2.3	2.0	6.3
Malaysia	RAS HVAC Cooling Total	12.6	2.6	95.8
	RAS HVAC Heating Total	0.0	0.0	0.0
	HP HVAC Heating Total	0.0	0.0	0.0
	HP HVAC Cooling Total	0.6	0.4	2.9
Durban	RAS HVAC Cooling Total	12.3	7.8	65.5
	RAS HVAC Heating Total	0.3	0.3	0.3
	HP HVAC Heating Total	12.9	12.9	26.3
	HP HVAC Cooling Total	2.2	1.9	6.8
Florida	RAS HVAC Cooling Total	12.5	10.6	61.9
	RAS HVAC Heating Total	1.9	1.9	0.9
	HP HVAC Heating Total	42.8	42.8	32.2
	HP HVAC Cooling Total	0.9	0.7	3.9
Portugal	RAS HVAC Cooling Total	10.4	7.7	36.7
	RAS HVAC Heating Total	0.5	0.5	0.5
	HP HVAC Heating Total	24.6	23.4	55.9
	HP HVAC Cooling Total	2.6	2.5	6.0

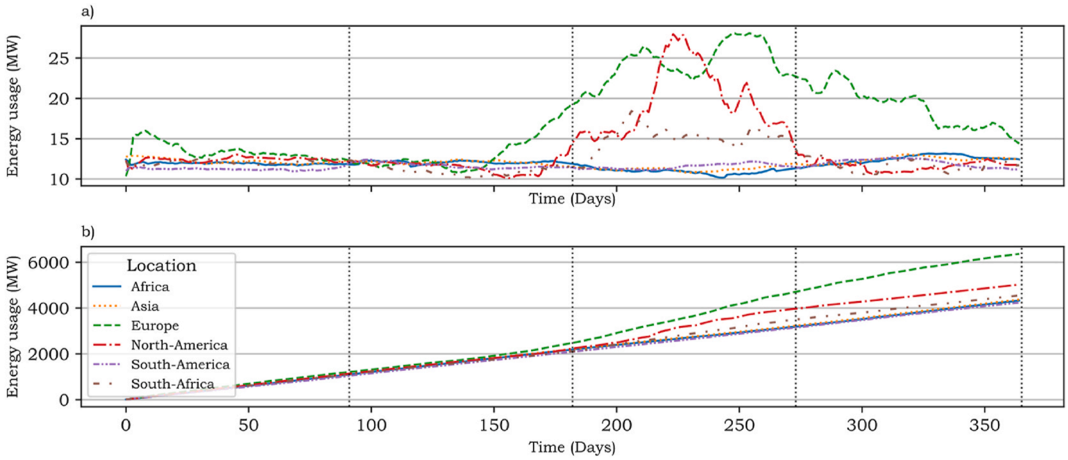

Fig. 5. Simulation results for (a) Total energy usage from all energy consuming components in the decoupled aquaponic system for the various regions. The Total system cumulative energy (b) is an indication of the system stock i.e., energy accumulation.

spiked which causes a peak demand of 18.4 MW. Given the humid and hot climate in the Durban region the results showed that Durban offers favourable climatic conditions when compared to global operations. The region provides competitive energy efficiency given the climate. Other regions in South Africa could still be suitable to operate aquaponic systems on large scale, however it might be less energy efficient.

3.4. Total system water usage

A negative value of the mass balance indicates a water deficit, and that the system is consuming water. A positive value indicates that there was a water surplus which was stored in a tank and used in the process in the future. Region humidity and air temperature played a major role in driving the water usage. The higher the humidity the lower the evapotranspiration rate and the less water will be lost. However, the higher the air temperature the higher the evapotranspiration rate and more water will be lost. The higher the external humidity the higher the condensation rate and the higher the water gain in the system. The simulation results are illustrated in Fig. 6.

Malaysia was the top performing country with 1209.1 × 10^3 m^3 of water return. This value was more than double the yield of the closest competitor which was Nigeria with a water surplus of 556.9 × 10^3 m^3. The top performing region in South Africa, Durban was second to last performing country globally with a net water return of 124.8 × 10^3 m^3. This was 89.7 % less water return compared to Malaysia.

South Africa had 65.3 % less water returns than the region that was ranked 4th, Brazil with a water return of 359.2 × 10^3 m^3. This indicated that although Durban has a hot and humid climate it still performed poorly compared to global locations. This was due to the fact that South Africa is a water scarce country and even within the humid climate

Table 4
Top performing countries with regard to total system energy usage.

Region	Rank	Peak Energy Demand (MW)	Cumulative Energy Consumption (MW)	Percentage underperforming (%)
Floresta Brazil South America	1	12.6	4239	0
Abuja Nigeria Africa	2	13.1	4330	2.1
Alor Setar Malaysia Asia	3	13.1	4372	3.1
Durban South Arica	4	18.4	4550	7.3
Orlando Florida North America	5	27.9	5240	23.6
Lisbon Portugal Europe	6	28.1	6370	50.3

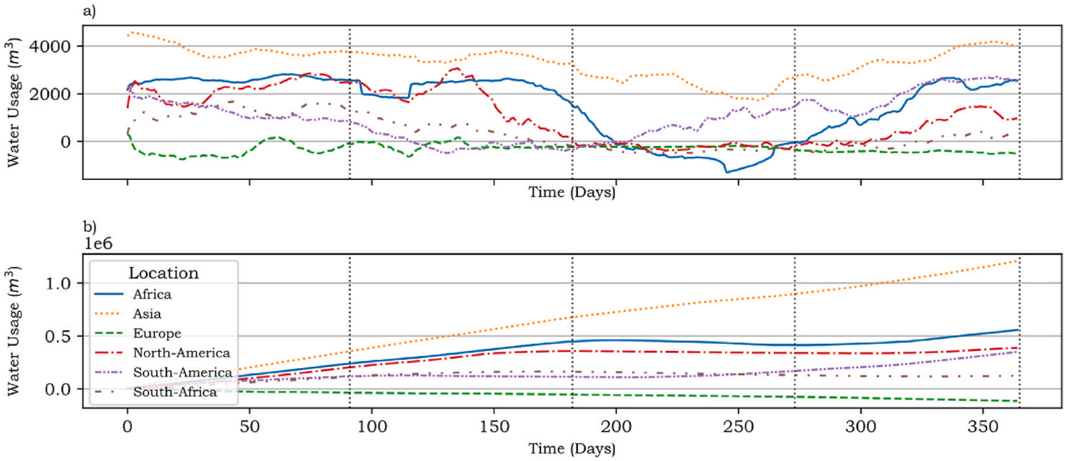

Fig. 6. Simulation results for total water usage (a) in the decoupled aquaponic system for the various regions. The total system cumulative water (b) is an indication of the system stock i.e., water accumulation or consumption.

Table 5
Top performing countries with regard to total system water usage.

Region	Rank	Water Usage (10^3 m^3)	Percentage Underperforming (%)
Malaysia (Asia)	1	1209.1	0
Nigeria (Africa)	2	556.9	53.9
Florida (North America)	3	387.9	67.9
Brazil (South America)	4	359.2	70.3
Durban (South Africa)	5	124.8	89.7
Portugal (Europe)	6	−114.3	109.5

water usage should be carefully managed. The water usage results are summarised in Table 5. All simulated regions expect for Europe had a net water return to the system, this was due to a limited requirement for cooling.

Regions which had high cooling demands were the regions where the most water was returned in the system. Cooling allowed for dehumidification of the air by means of condensation on the cooling coils. This occurred when the supply air temperature reached levels below the dew point which caused the moisture to be removed from the humid air. Since humid conditions were experienced throughout the year in regions such as Malaysia, Nigeria, Florida and Brazil and these regions required continuous cooling, water was captured during the dehumidification process. From all the regions that were compared in South Africa, Durban's climate can be compared with the best performing global regions as presented in this study.

The results revealed that regions that experienced high temperatures and high humidity for prolonged periods throughout the year had the best energy performance. Countries close to the equator such as Malaysia, Brazil and Nigeria exhibited little difference in temperature and humidity experienced throughout the year. The constant high temperatures and humidity caused more uniform energy demand profiles throughout the year. Minimal heating was required for these regions and cooling was the dominant energy contributor. It can be concluded that regions that experience tropical climates are the most suited for aquaponic systems with regard to energy usage.

The outcome of the research further showed that top performing regions in South Africa compare relatively well to international locations with regard to energy and water usage. In context of the defined system and conditions described in this research commercial aquaponic systems in South Africa could have relatively good energy and water efficiency compared globally. The results motivate that the best region to operate such systems would be tropical climates as experienced in the eastern coastal regions of South Africa, where high humidity and temperatures are experienced.

4. Conclusion

This research has investigated the viability of aquaponics systems design and development in South Africa and a few other nations without a previous energy efficiency data of their geographical location for aquaponic systems design and development resulting in some inherent limitations. Analysis and evaluations were conducted in respect of the city with the most efficient energy level for aquaponics systems design in such nations as South Africa and Nigeria on the African continent. Finally, a generalised holistic model premised on System dynamics for the computation of energy efficiency of aquaponics systems design was presented.

System dynamics modelling and systems thinking methodology was applied to represent a generic decoupled aquaponic system. The method aided in capturing the system holistically in respect of energy and water usage in a complex system where there are a lot of variables resulting in system complexity. The models provided valuable insights into the effects of local climatic conditions on a generically defined decoupled aquaponic system. Local climatic factors such as the ambient air temperature, relative humidity and incoming solar radiation played a major role in system stock variables such as energy and water usage. This was demonstrated by the fact that environmental control, which was heavily affected by external conditions, contributed 99 % of the total system energy usage.

As part of the inherent limitations herein, it is recommended that more weather data is captured and used to increase the accuracy of the developed models. Furthermore, Beyond the use of SD, other energy improving strategies can also be incorporated into the model and the effects of the strategies can be investigated. These strategies can be the incorporation of system heating by means of process waste heat, or thermal storage techniques and evaporative cooling technology. The different strategies can be compared to determine the best solutions. The system dynamics model can be altered to account for all the changes in the system due to the energy improving techniques. This could add a delay element to the system and valuable observation could be produced.

The research does not comment on the success of a commercial scale aquaponic system based on location but rather investigated where it will operate the most efficiently. The results produced a recommended region but does not provide insight into the extent of regional change. The location can be further narrowed down to an optimal location within the region of Durban. It is recommended that the results of this research are tested and verified using experiments on at least small-scale operations. It is also recommended that more weather data that could be used to increase the accuracy of the produced models be captured. With more data obtained from a variety of weather stations, the estimation error can be reduced and the results will be more reliable. Currently, there is a lack of reliable data in South Africa, which could exert a negative impact on the results. It is therefore important to gather dependable data to draw better conclusions. For instance, Durban was identified as the most suited region with regard to energy and water. Even though this region proved to be the best performing region, other regions could still provide successful operations.

The research can be extended by investigating the effects of energy-improving strategies on the total system energy usage. Given a selected location where the basic weather data trend is known, other parameters could be varied, and the system response could be observed. Parameters such as internal environment set points could be altered to investigate the optimal internal environmental conditions. Furthermore, material properties can be varied to determine location specific optimal material selections.

Furthermore, the values of U4RIA, an acronym credited to the Climate Compatible Growth (#CCG) programme, depicting: Ubuntu, Retrievability, Reusability, Repeatability, Reconstructability, Interoperability and Auditability were integrated into this research. Ubuntu herein, was upheld via community economic empowerment through the provision of efficient water and energy utilization scheme for an integrated cropping and animal system. A policy on this environmentally friendly and sustainable mixed controlled scheme can be highly beneficial for the economic empowerment of poor societies and creation of jobs for the unemployed in today's world of exploded population, inflated cost of living, high level of unemployment and an ever growing level of crime. The symbiotically controlled system which harnesses the potentials of the ambient environment speaks to the United Nations sustainable development goals number 7 (affordable and clean energy) and 13 (climate action) respectively. Retrievability in this research was achieved by putting in place, an adequate archiving system of resource materials, data and results with a mission tailored towards easy accessibility. A future policy formulation or enhancement in respect of aquaponics system in developing economies such as the African continent amongst others can easily recall and utilize the findings of this research. Reusability in this research is premised on the ability to adopt barely the same set of model variables, parameters and governing conditions for a future research that seek to explore the viability of an aquaponic system in other nations of the world. Repeatability herein was facilitated through adaptability of the same energy efficient model to new investigations with the change of parameters only. Reconstructability was achieved by creating room for modifications and improvement using the same design logic. Interoperability was achieved through systems thinking and dynamics. These cascaded concepts, speak to integratedness of system elements in modeling. Diverse factors interconnected towards energy efficiency for a sustainable aquaponics system was identified from a holistic point of view and built into an integrated model that functions as a single unit for effective energy policy. Auditability herein is premised on continuous monitoring and accountability of quantitative outputs such as energy utilization and power consumption, CO_2 emissions to the environment and water level losses amongst others.

CRediT authorship contribution statement

Adriaan J.G. Roux: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Michael K.O. Ayomoh:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review & editing. **Venkata S.S. Yadavalli:** Conceptualization, Project administration, Writing – review & editing. **Ramesh C. Bansal:** Conceptualization, Project administration, Writing – review & editing.

Declaration of competing interest

no conflict of interest statement.

Acknowledgments

The authors acknowledge supplementary support from the Climate Compatible Growth Program (#CCG) of the UK's Foreign Development and Commonwealth Office (FCDO). The views expressed in this paper do not necessarily reflect the UK government's official policies.

Appendix A

The full causal loop diagrams of the respective systems are included as an appendix given the size and complex system intricacies of the decoupled aquaponic systems. All reinforcing and balancing loops are illustrated as discussed in the main text.

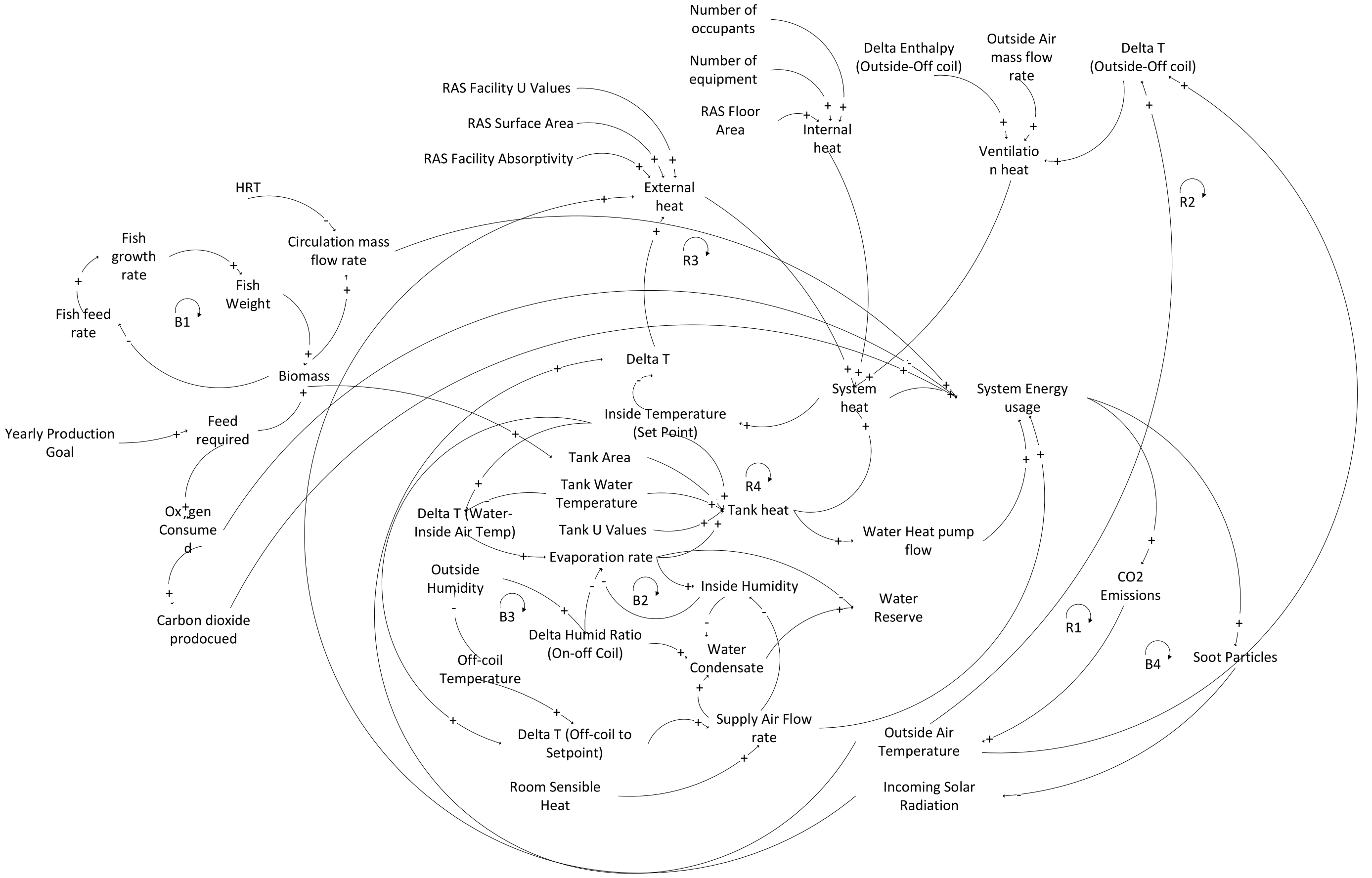

Fig. A.1. Causal loop diagram indicating the system cause-effect and feedback loops of the various system components for the recirculating aquaculture system.

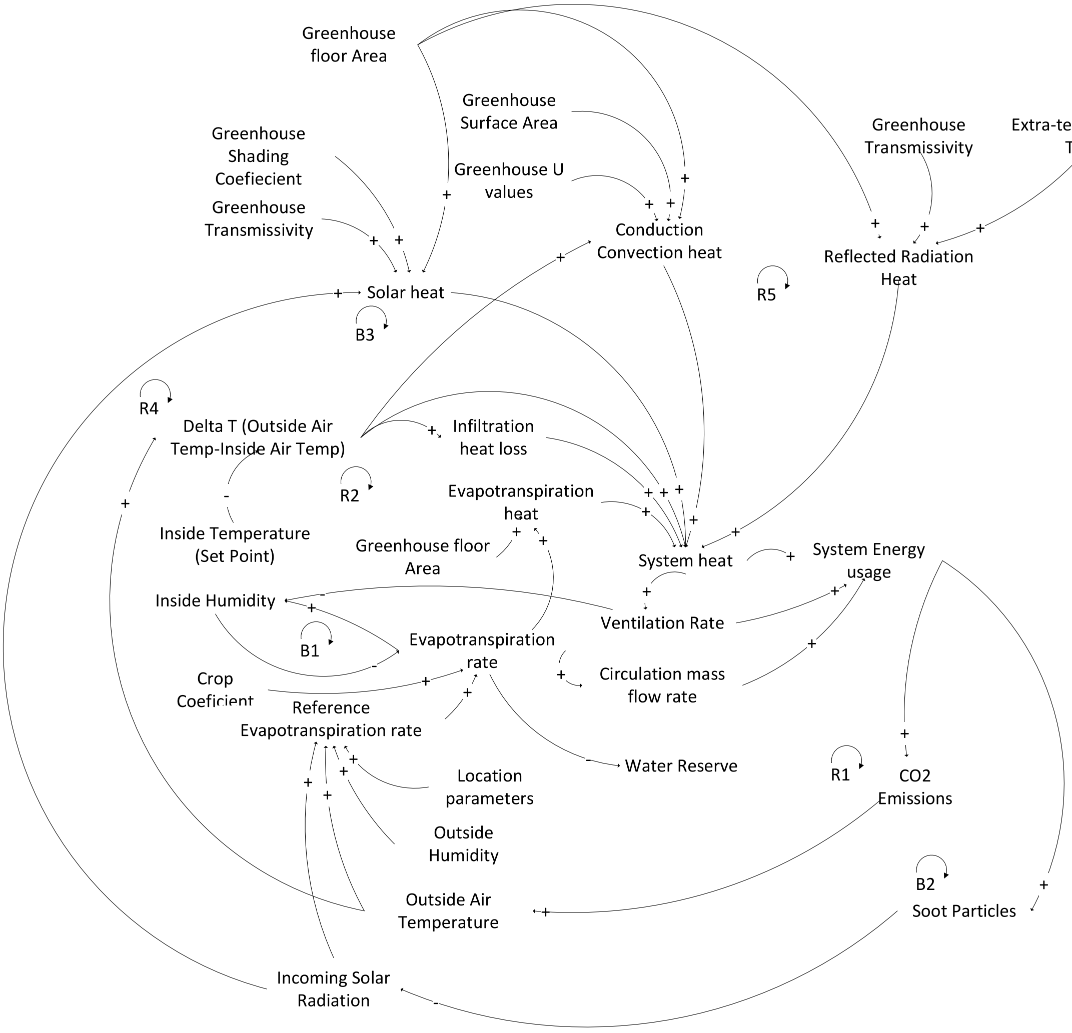

Fig. A.2. Causal loop diagram indicating the system cause-effect and feedback loops of the various system components for the hydroponic greenhouse.

Data availability

The used data is contained in the uploaded manuscript.

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