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A Simplified Design Process for Thermal Supplementation of a Medium Sized Aquaponics System to Ensure Sustainability

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Abstract

Growing climate change awareness incentivizes establishment and implementation of efficient alternative food production methodologies such as aquaponics, with potentially high yield versus reduced footprint, urban implementation and local food security and employment. Viably maintaining such systems during freezing winter climate necessitates thermal supplementation to maintain biological viability of the fish stock and bio-filter micro-organisms. The purpose of this study is to present a simplified baseline approach for determining thermal supplementation for establishing sustainability of a medium sized aquaponics system. An existing aquaponics system is examined and described through historical temperature data, system thermal interaction via mass-flow loop energy transfer and a physical layout. Applicable historical measurements for initial supplementation determination are be listed. The chosen solar supplementation source is discussed in terms of cost and energy input. Further examination of study data informs system energy interaction and system micro-biota viability. The presented method results in an inter-cold-front positive system temperature recovery slope of $0.278^{\circ}C$ *per day and an extrapolated temperature buffer recovery in 15 days, validating the viability of the method as presented. The value of adopting this method lies in promoting aquaponics system adoption by simplifying system-viability supplementation estimation where direct grid energy unit-cost comparison allows for informed decisions. Adopting the method for the Bloemfontein area, or locations with similar climate, is thus recommended.*

Key-words: Sustainability, Solar.

1. Introduction

Diminishing food security and increased population would suggest a general adoption of aquaponics systems, due to their increased yield and water efficiency as [1] clarifies. Climate change predictions [2] indicate special relevance of such systems to arid southern-African regions, including Bloemfontein in South Africa, as [3] shows.

Aquaponics expands established hydroponics to include fish in the cycle. Ammonia compounds produced by aquatic fauna is broken down to Nitrites and Nitrates by bio-filter micro-organisms, the nitrogen-rich water feeds the plants, returning clean water to the aquatic component. Compact implementation and sustainable closed-cycle aspect promotes urban adoption [4] which directly impacts local food security, job creation and economic empowerment as [5] examines. Additional benefits include a reduced carbon footprint, lower fertilizer input, minimized water wastage and ready scalability [1]. The fresh produce promotes health and the fish protein serves as a source of amino acids beneficial to adolescent cognitive development [6], especially significant in poor rural communities [7]. Promoting urban and rural aquaponics adoption, and especially in terms of a skill-transfer integration into African traditional agricultural method, is therefore of rising importance to timeously disseminate this knowledge and equip a new generation to become more sustainable in terms of food generation.

Sustainably maintaining aquaponics systems in areas which experience freezing winter temperatures, presents challenges. The biological viability of the aquatic fauna, as pertaining to temperature, is species dependent. In addition, the micro-organisms in the bio-filter may die below 7˚C [8]. Aquaponics' circular nature means that a break in the chain (such as micro-organism die-off) causes system toxicity build-up. It is thus necessary to thermally supplement such aquaponics systems in areas of extreme cold, where freezing temperatures can occur. It is also desirable to quantify the sub-system thermal interaction, directly indicating areas for further potential thermal loss mitigation and cost savings. The purpose of this study is to present a simplified baseline approach for determining thermal supplementation for establishing sustainability of a medium sized aquaponics system.

Firstly, potential thermal supplementation methods will be examined. Secondly, a simplified historical-data approach to initial determination of required system energy input will be presented, coupled with the description of the system energy exchange interaction in terms of its mass-flow power transfer. Thirdly, supplementation will be examined as relating to the system biological viability and sustainability by way of data interpretation. Fourthly, benefits of a monitoring system in refining

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understanding of the system thermal interaction is investigated, and applicability to thermal interaction of different system topologies considered. Anticipated results, discussion and conclusions then follow.

2. Literature Review

Aquaponics system implementation is varied, yet scalable with system size varying from hobby implementation to large-scale commercial enterprises. Of interest in the South African (and specifically Bloemfontein in the Free State Province) context, and mindful of the issues surrounding economic empowerment and establishment of local food security, is the supplementation requirement for medium-sized aquaponics systems. A local retrofitting opportunity exists for existing dams that maybe considered ‘medium’ size reservoirs of between 10 kl to 100 kl. This criteria also informs the focus of single-loop, rather than multiple decoupled loop system topologies, as [1] informs.

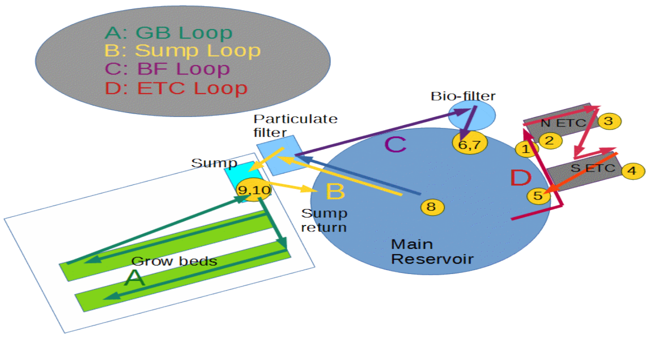
Aquaponics systems may typically require both electrical (e.g. continuous water pumping) and thermal (typically water heating in winter time) energy input. Rising electrical heating costs and the unreliable nature of the electrical grid supply in South Africa makes it desirable to investigate other supplementation methods. A comprehensive study by [9] investigates alternatives, including photovoltaic and solar thermal modules, wind turbines, hydropower, biomass converters, heat pumps, gas boilers and interfacing to the electrical grid. Cost-effectiveness and least-cost methods, as well as suitability of harvesting methods are listed and renewables highlighted.

Functionally, an aquaponics system may be represented by the main reservoir (a dam for aquatic species), the bio-filter (micro-biota habitat) and the grow-bed(s) (plant produce cultivation). Circulating pumps, filters and water aeration maintain a viable environment. Thermal modelling of complex dynamic systems also containing an active biological component is potentially computationally complex, as [10] opines. Consideration of [11] suggests some applicable approaches to quantifying thermal supplementation, and draws attention to the requirement for a uniform temperature distribution in the main reservoir. Of further note is the impact of optimizing main reservoir temperature in order to maximize fish growth, as [12] have detailed for a range of temperatures. Maximized fish growth throughout the year is considered desirable, and impacts the choice of supplementation strategy, if so implemented. An electronic monitoring system is a requirement to enable evaluation of the results, where relevant system temperature data may be logged to Google Sheets. Local monitoring of the data may be achieved via Bluetooth to a generic Android device serial terminal application.

3. Quantifying Sub-system Thermal Contributions

Describing an aquaponics system in terms of the sub-system thermal contribution is advantageous, and has the benefit of potentially identifying areas for optimizing thermal loss mitigation. The various components are typically physically separate and exposed to varying energy exchange to the ambient surround, requiring mention of some relevant criteria to the simplified supplementation design process: Water exchange flow rate between the main reservoir and bio-filter component is typically high, up to one third of the main reservoir volume per hour is desirable. Furthermore, the bio-filter volume required for sufficient ammonia compound breakdown is small in comparison with the main reservoir [1]. Presuming nominal close proximity of these components, therefore, implies a small temperature difference. The assumption that the main reservoir temperature may be utilized as a system temperature base calculation reference is thus justified. As Figure 1 illustrates, there are many points of temperature monitoring interest in a basic aquaponic system. The figure describes the supplemented layout as presented by [13] and lists temperature measurement points for water entry- and exit used to describe the mass-flow energy transfer of each water flow loop.

Figure 1 - Example Aquaponics System Flow Loops, Illustrating Potential Temperature Measurement Points, Reproduced from [13].



Simply summarised, the main aquatic reservoir temperature is the sum of its' ambient exchange (i.e. convective, evaporative and radiant losses and gains), and the contributions of each returning water flow loop in terms of power transferred (i.e. energy change). This may be expressed as follows:

$$P_{main} = P_{atm} + P_{bioftr} + P_{sumpret} + P_{suppl} \qquad (1)$$

Where:

- *Pmain* = total power change of the main aquaponic reservoir;
- *Patm* = the main reservoir thermal exchange to ambient surround;
- *Pbioftr* = the bio-filter mass-flow loop power contribution;

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- *Psumpret* = the sump return mass-flow loop power contribution; and
- *Psuppl* = the supplementation return mass-flow loop power contribution (note that this term may not necessarily be a 'flow' return, but is still a kWh contribution from any other source).

These are stated in terms of kWh energy gains or losses: as grid-supplied power is sold in kWh units, this is a readily interpreted reference. Recall that in terms of S.I. unit equivalence, 1 kWh equates to 3.6 MJ. As the main aquaponic reservoir is used as the basis for calculation reference, it is also desirable to state the total power contributions in terms of its temperature change, and vice versa:

$$Power\ loss = \frac{cp * T * m}{t} \text{ Wh} \qquad (2)$$

Where:

- *cp* = the specific heat of water and is assumed to be 4.184 $J.K^{-1}.g^{-1}$;
- *T* = represents a measured temperature difference in degrees Celsius or Kelvin;
- *m* = the main reservoir water mass in kg; and
- *t* = time.

The preceding section suggests that a simplified approach to initial sizing of the required supplementation would be as follows:

- Step 1: Determine the volume of water in the main reservoir (this may generally be readily obtained for manmade structures, typically applying basic mathematical equations). The water mass may be assumed to be 1 litre = 1 kilogram, and fulfils the term '*m*' in equation (2);
- Step 2: For existing aquaponics systems, gather some historical site reservoir temperature data, specific to the site reservoir and active system as incorporating the grow beds and bio-filter, as outlined below. This satisfies the term '*T*' in equation (2). Note that this value comprises by implication the sum of '*Patm', 'Pbioftr' and 'Psumpret'* in equation (1). For retrofit purposes, gather the same data for the intended main reservoir, representing only '*Patm'* in equation (1). This preparatory data may be gathered manually with a thermometer(s);
- Step 3: Apply a suitable required daily temperature gain in terms of the reservoir water mass, using equation (2), to determine the minimum required power input in kWh. Note that 'daily' by implication satisfies the term '*t´* in equation (2). This required temperature gain is further detailed in the next section discussing 'positive recovery slope' and 'temperature buffer'. If the application is a retrofit aquaponics implementation (implementing a new aquaponics system to an existing dam structure), the terms '*Pbioftr*' and '*Psumpret*' from equation (1)

will not be known. These may, by estimation, be compensated for if data from a similar grow-bed in the area is available. Data for the study site in the Bloemfontein area, listed in a later section, shows the dynamic thermal contribution for its' specific construction, size, orientation, flow rate and system configuration; and

- Step 4: Implement a monitoring system to enable evaluation and verification of the results.

The site temperature data so gathered should include the maximum day-to-day temperature drop, which should coincide with minimum insolation (i.e. the winter solstice, which is 21/22 June in the southern hemisphere), where possible. Measurements should be taken daily, at a set time coinciding with the commencement of insolation at the site (i.e. temperature rise- or harvestable sunshine early in the morning). Of direct consideration is the average day-to-day temperature drop as determined by this datum set, around the previously identified 'critical' bio-filter temperature-limit of 7˚C. A multi-year collation of site-specific temperature maxima and -minima is also desirable at this stage, as differentiation between averaged daily expected winter minimum temperatures, and extreme cold events is of import. Such extreme events might be better accommodated by additional electrical supplementation, or other mitigation strategies. Determination of a suitable method for supplementation may now be made, with criteria such as cost, implementation constraints, predicted system life, predicted yield income, maintenance, etc.

It should be noted that choosing an ETC supplementation approach may mean long term savings gained at the cost of flexibility in coping with extreme temperatures. This does not preclude additional electrical supplementation, with no implied running costs otherwise. The recent study by [13] into thermal supplementation of an existing aquaponics system in the Bloemfontein area in South Africa serves as example of such historical temperature data, gathered for a 42 kl main reservoir active aquaponic system. Their maximum site-specific historical day-on-day loss was 0.97˚C, while their average historical loss slope around the bio-filter temperature-limit of 7˚C was ≈ 0.25˚C per day. These inform further discussion around a supplementation determination:

It is desirable to exceed the average daily loss slope as determined by the gathered historical data, as the system needs a positive temperature recovery slope to regain temperature, not just maintain it. This average daily loss slope is the average day-on-day main reservoir temperature loss around the 7˚C critical main reservoir temperature, as experienced during cold weather. The magnitude of the recovery slope is informed by the maximum day-on-day temperature loss observed, and considering long term collated temperature data for the site area, of which [14] is a common source. Examining such site-specific long-term data, [13] noted that a temperature buffer of 3˚C would be suitable for their study. This buffer represents the amount of degrees Celsius by which the main reservoir temperature would drop during a passing cold front, and thus the required temperature rise (buffer) above the 7˚C minimum main reservoir temperature. To summarise: the magnitude of the temperature buffer relates to the positive recovery slope in that the daily temperature rise required should re-establish the identified temperature buffer within the identified inter-cold front time period.

Having thus determined the required daily system thermal supplementation requirement, realizing supplementation presents the choice of implementation methodology. In their site-specific study, [13] determined that supplementation was possibly needful over about a two-and-a-half month period; thus their potential total energy required approximates ~1830.45 kWh. In South Africa, electrical grid energy is supplied at different rates. The 1830 kWh may imply roughly a R2 (or 0.13 $ at an exchange rate of R15/1 $) cost per kWh unit or in excess of R3600 (240 $) supplementation cost for the winter period only. Consider that the temperature may be required to be optimal for species growth maximization throughout the year, thus extending the required supplementation period and costs. The implemented supplementation choice for the [13] study thus becomes clear – ETC systems are installed for long-life low-maintenance, with once-off installation cost and low running costs (a small sub-kW pump, for example), while grid-supplied energy costs are high and continue rising. The intended lifetime of the aquaponics implementation should be considered, as the initial installation costs will be amortized through the planned lifetime.

It must also be noted that if implementing ETC supplementation, then the site-specific insolation for the period of temperature buffer establishment becomes relevant. Such may be evident when local historic weather data are collated for any planned aquaponics system implementation, when evaluating for similar climate locations.

In the system implemented by [13] the ETC flow was directly returned to the main aquaponic reservoir. With some prior preparation, such a supplementation system may be set up in a matter of days, including a suitable control system. In Figure 1, this is indicated by the red ‘ETC Loop’ section (two sets of 40 ETC tubes, a pump and electronic monitoring and control).

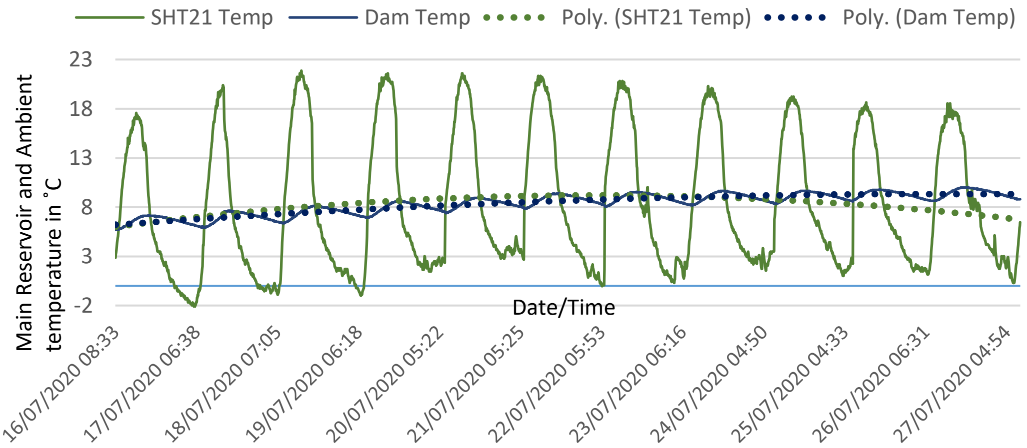
4. Benefit of Implementing a Monitoring System

Having discussed the simplified design process above, it is now necessary to address the benefit of implementing electronic monitoring of the system. Strictly speaking, any supplementation towards system viability, regardless of choice of source energy, only needs to cater for the identified ‘buffer’ temperature value and ‘positive recovery slope’ as previously discussed. If grid electric energy is used, it need only be used until the main reservoir temperature reaches the minimum predetermined value of

7˚C plus the chosen buffer temperature, and then to maintain it sporadically. If ETC- or PV-derived energy is used, there is no additional direct cost involved in raising the temperature even further. In order to interpret the system energy interaction a continuous monitoring scheme needs to be implemented. Such data would typically be derived from monitoring the various loop-flow energy contributions, with functional flow loops as illustrated in Figure 1. Determining water flow return energy transfer necessitates differential temperature- and flow rate determination of each flow component (e.g. Figure 1, loops B, C and D). The study by [13] further examines this energy transfer determination.

An example of such temperature measurements are shown in Figure 2, for the period 16 July 2020 to 27 July 2020. This illustrates both the daily dynamic nature of the reservoir change (serving as illustration of the importance of consistently measuring a reservoir under investigation at a specific hour), and the temperature recovery slope (5.75˚C to 8.81˚C, over an eleven-day period) of 0.278˚C per day. Note the orange trend-line (for SHT21 Temp) indicating the ambient measured temperature trend, and the blue trend line (for Dam Temp) graphically indicating the system main reservoir temperature recovery slope.

Figure 2. Graphic representation of atmospheric and main reservoir temperatures for the period 16 - 27 July 2020



This corresponds very well with the identified recovery slope/buffer temperature criteria previously discussed. Of specific note is that the initial 5.75˚C minimum temperature of the graph is below the identified 7˚C minimum system requirement. Table 1 lists site-specific ambient temperatures for the Bloemfontein district, as obtained from [14]. It illustrates the unusual severity and extended duration of a cold front event. An explanation for this highlights the previous discussion regarding the requirement for a multi-year collated temperature history for the specific site location. The 2020 winter

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season in Bloemfontein was particularly severe, with below average night-time temperatures, and multiple extended ‘extreme’ cold weather events [15, 16]. These are typically characterized in Bloemfontein by the passing of a ‘cold front’ (cold Antarctic weather systems moving across the southern tip of Africa). The datum subset selected and presented was specifically chosen to highlight and show this ‘worst-case’ scenario. Both the temperature recovery slope and the temperature buffer establishment time are as intended by the design method, and indicates that the system recovery behaviour matches the supplementation criteria established. The chosen buffer establishment, extrapolating from the period-specific 0.278˚C per day temperature recovery slope, would take approximately another 4.3 days (15.3 days total).

Table 1 - Site Temperature Data for the Period 14-27 July 2020, as obtained from (AccuWeather)

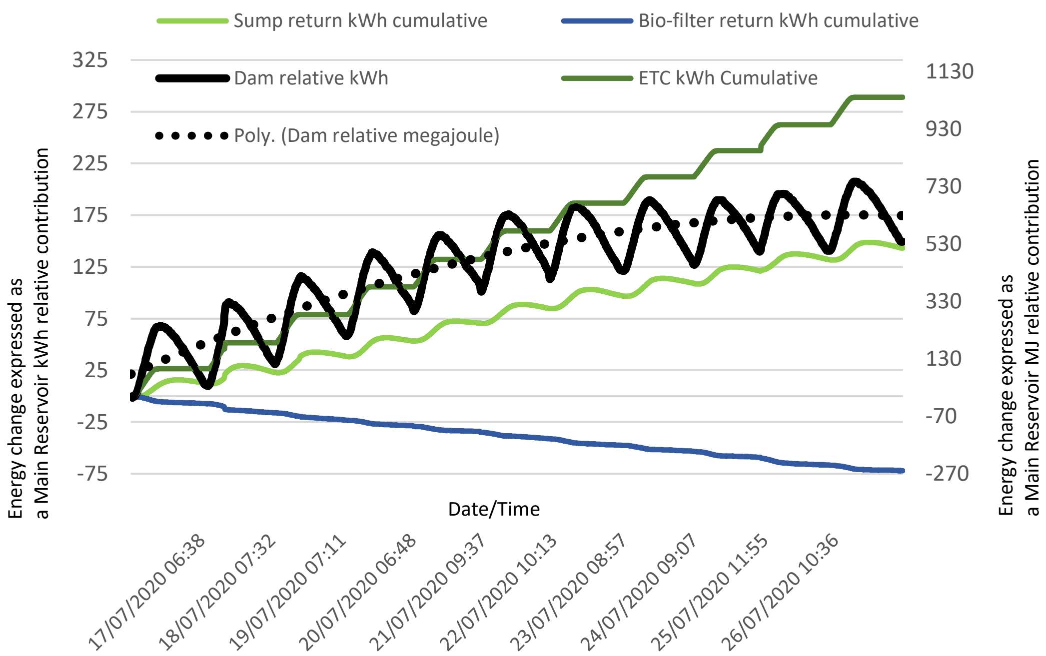
	14th	**15th**	**16th**	**17th**	**18th**	**19th**	**20th**	**21st**	**22nd**	**23rd**	**24th**	**25th**	**26th**	**27th**
Max℃	9	15	21	23	23	24	23	22	22	21	20	19	19	19
Min℃	-6	-9	-10	-9	-7	-7	-6	-6	-6	-6	-6	-5	-5	-3

The further benefit of a monitoring system that reports loop differential temperatures may be seen by examining Figure 3, which depicts the cumulative power change in the main reservoir (in terms of the previously established nomenclature, the energy change with 1 kWh = 3.6 MJ) and loop contributions, for the period 16 to 27 July 2020. Note the black trend line indicating the system temperature recovery slope expressed as a kWh value and MJ value. In Figure 3, which corresponds to the time period in Figure 2, the relative power change (energy change) of the main reservoir and sub-system contributions were shown. Figure 3 depicts a relative cumulative contribution over the period, i.e. starts from a common reference point (0 kWh or 0 MJ). The benefit of this representation immediately becomes clear, as the dynamic weather-dependent energy cost of each sub-system is readily apparent. It allows direct comparison to grid energy purchase costs, and has some further notable implications:

- The grid-cost equivalent allows comparison of potential solutions;
- The dynamic mass-flow evaluation of system improvements or changes allow immediate evaluation;
- The grid-cost depiction allows for visual insight into the potential benefit of system changes (referring to Figures 1 and 3: physically relocating the bio-filter into the grow-bed enclosure would yield immediate benefits: the grow bed thermal solar absorption (the main reservoir kWh energy input via the sump return flow, Figure 3) yields generally positive net daily benefit. The exposed bio-filter loss over the depicted period is ~75kWh);

- Referring to equation (1) and comparing it to Figure 3, the relationship between the various sub-systems and main system temperature is readily understood;
- The method is applicable to various system layouts and types;
- The sub-system analysis via mass-flow power transfer is readily scalable to multi-loop systems; and
- The representation allows visual appreciation of sub-system energy cost contribution and informed decision regarding system energy cost decisions in terms of grid energy cost.

Figure 3 - Graphic Depiction of System Thermal Interaction Represented in Terms of kWh and MJ



The enclosed grow-bed in the system under investigation [13] acts as a thermal 'battery' during extreme cold weather events, with a net positive influence on the main reservoir, as returned through the sump-return flow. This effect is visually apparent through representation such as in Figure 3, and may only be readily quantified with an electronic monitoring system in place. Note that the grow bed enclosure(s) may differ in size, height, construction, orientation, placement, water flow and surrounding area influence – this will of necessity be a method yielding growing success as more systems are detailed in literature and/or monitored electronically. This would enable increasingly accurate corrective factors for the retrofitted implementation of aquaponics systems to the dams on small holdings in the Bloemfontein area.

The method used to determine a suitable supplementation value is suited to implementation with existing aquaponics systems, and may be used in other topologies such as multiple-loop grow beds. Note that as system topology changes, inherently dynamic sub-system energy transfer to the main reservoir will also proportionally change. This illustrates the importance of implementing an electronic monitoring system, in order to determine the magnitude of these sub-system thermal effects vis-à-vis their mass-flow power-transfer to the main aquaponic reservoir. The implementation of such a monitoring system, with real time online data, promotes the potential adoption into the idea of 'Sustainable Smart Cities'. The studies by [17, 18] further inform the benefit of cloud-based real-time sensor data and IoT aquaponic systems monitoring.

5. Conclusion

The purpose of this paper was to present a simplified baseline approach for determining thermal supplementation for establishing sustainability of a medium sized aquaponics system. The results represented in Figure 2 indicate the expected system thermal recovery and establishment of the temperature buffer. A similar result can be expected when implementing a simple temperature-based supplementation switching scheme (i.e. on/off on-demand based on a thermostat in the main reservoir) or using an ETC supplementation scheme, with, for instance, a simple daylight-switch for supplementation activation.

In order to further refine results and gain insight into the sub-system thermal contribution, via the water-loop mass-flow energy transfer method, an electronic monitoring system is indicated, enabling examination of the results as in Figure 3. The dynamic nature of the sub-system thermal response does not otherwise readily lend itself to manual non-automated measurements.

During winters exhibiting climate such as in the Bloemfontein area, the method described is expected to yield reliable supplementation results in terms of the system biological integrity and avoidance of species mortality. In areas experiencing similar climate challenges, and using the method described as a baseline approach, positive results may be expected. Furthermore, implementing a detailed monitoring system as outlined, targeted system improvements may be made based on the detailed depiction of thermal cost expressed in the same manner as grid energy cost (i.e. kWh grid energy procurement).

Choosing to adopt a similar solar ETC supplementation method results in long-term cost savings and inherently avoids reliance on grid power consistency, at the cost of flexibility in dealing with extreme cold events. However, additional electrical supplementation is certainly readily achievable, in order to assure continued bio-filter micro-biota sustainability. The lure of an increased grow season and improved yield is expected to appeal to commercially minded potential adopters of aquaponics.

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