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MICROGRID POWER MANAGEMENT WITH INTEGRATED QUALITY OF LIFE CONSIDERATIONS

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NOMENCLATURE

C : Condition
CI : Community Importance
ED : Energy Dependence
W : Weight
P : Power (kW)
t : Time (hours)
L : Energy Load (kWh)
d : Deviation variable
S : Energy Storage (kWh)

ABSTRACT

Electrification can act as a catalyst in social progress. In some communities, grid connection is not possible. As such, microgrids are a viable alternative to provide access to electricity. Yet, progress can be impacted by challenges with insufficient energy supply. In such scenarios, it is important to understand the relationships between electricity supply and social development in managing available resources.

We propose a framework to relate quality of life with power management, such that progress is not hindered when available energy is insufficient. In this paper, electrical loads for pumping water, powering streetlights, and powering household devices are examined. A compromise decision support problem (cDSP) is developed to balance the produced and consumed energy. We develop a set of power management options by exploring the solution space developed from performing the cDSP, anchored in quality of life. Organizations engaged in sustainable development can select the solution most appropriate for the community.

A salient feature of the framework is the versatility. The formulation can be modified for different requirements, communities, and time periods. A test problem is used to illustrate the flexibility of the approach. This framework is constructed to support decision making for microgrid operation to continue to uplift communities.

1 FRAME OF REFERENCE

Access to electricity can facilitate progress in developing communities [1,2,3]. Electricity can power devices that support different aspects of life. This is achieved by improved quality of life through positive impacts on education, health, agriculture, and safety [2,3,4]. However, more than a billion people in the world still do not have access to electricity. In many rural communities, grid access is limited or costly to implement [5]. In these instances, microgrid systems are very effective. Microgrids are typically composed of a generation, distribution, and transmission system connecting to energy loads. Still, challenges associated with supplying energy to meet needs exist. For off-grid communities, renewable energy sources are used in power generation. The intermittent nature of such energy sources can result in insufficient available energy. When the supply of electricity is insufficient in meeting the amount demanded, progress can be stalled or negatively impacted. Thus, power management is significant in ensuring available resources support the energy demand. Lloyd et al. [4] examines social upliftment and discuss the positive impact of electrification through reduced health hazards and difficulty of general household activities. The positive impact of electrification on education and poverty alleviation is affirmed in [2] and [6]. However, solutions that consider long term sustainability and empowerment is not necessarily addressed. From these studies, we recognize access to electricity can be transformative for well-being.

Well-being is frequently assessed by the level of needs satisfied. Maslow’s Hierarchy of Needs and Max-Neef’s Fundamental Human Needs are two common methods of defining needs [7, 8]. Maslow’s Hierarchy defines levels of needs from basic to complex using a hierarchy [7]. This hierarchy has become less appropriate. For example, there may be cases where education is accessible, but clean water is not. Max-Neef defines fundamental human needs without a hierarchy [8]. These fundamental needs include; subsistence, protection, affection, understanding, participation, leisure, creation, identity, and freedom. Both Maslow’s Hierarchy and Max-Neef’s Fundamental Human Needs define basic needs and support an understanding of quality of life. Costanza et al. [9] examines the connections between quality of life, well-being, and human needs. Weighting, summation, and multiplicative relationships are approaches highlighted for quality of life assessment. The Human Development Index, Social Progress Index, Eurostat QOL, World Happiness Report, and Bhutan’s Gross National Happiness Index are methods used in ranking nations based on well-being [10-14]. These rankings are on the national level, however, a community within the nation may differ. Some of the indicators used in these rankings are health, education, and living standards. The parameters of these indices provide valuable information for promoting progress in comparison to the ranking. Principles for socio-technical design and design in the developing world are discussed in [15] and [16]. One of the themes of these studies is the necessity of understanding the setting and conditions. Yadav et al. [17,18] suggests the formation of tensions through dilemmas between social, environmental, and economic considerations. Yet, more work is required to adequately incorporate social considerations in technical systems. Socio-technical applications have been demonstrated within community development and energy systems. Baek et al. [19] examine a framework for community resilience and the formation of objectives for socio-technical design. This type of approach is imperative in creating solutions that support continued development. In a study by Akinyele, the challenges in solar power systems in developing regions are discussed and the need to include a social analysis of energy demand is identified [20]. We see the social dimension applied in forming design requirements, progress, and energy demand analysis. However, there is still a need to incorporate considerations to address the need to improve the quality of life. Therefore, a socio-technical model is necessary in resolving the problems arising from limited energy supply.

Examining the possible outcomes and modeling scenarios can be helpful in determining appropriate power management solutions. In a study by Palma-Behnke et al. [21] power management is approached by supporting demands associated with water and electricity, while minimizing cost. The current practices need to be enhanced to more effectively allocate available resources. Yet, development is not adequately addressed. We propose a framework for integrating quality of life considerations with power management. The perspectives within and across communities are unique. As such, technical solutions need to reflect and adapt to these perspectives. Examining the literature provides valuable information for pairing social and technical considerations in developing appropriate solutions. Socio-technical design concepts have applications in a wide variety of settings. However, there is a need to specifically relate quality of life parameters to microgrid design and operation. Investigating the literature has elucidated challenges with sustaining microgrid systems for rural development. The primary question is: **What mathematical relationships between social and technical systems are needed to support the sustainable, resilient operation of microgrid systems?**

2 FRAMEWORK

A framework for microgrid operation that uses community characteristics to support decision making is introduced in this section. In a previous paper by the authors, a quality of life model is developed to better understand community needs [22]. This model also connects the parameters defining quality of life to energy use. The power management model is then used to determine energy allocation options. Thus, the solution space is developed from pairing these two models. The framework is designed to provide support for human decision makers. An overview of the framework is visually presented in Figure 1.

Blocks A and C are not a primary focus in this paper, but provide context for the framework. Blocks B, D, and E are the main components discussed. Understanding the social, technical, physical, and environmental characteristics of the community corresponds to Block A of Figure 1. These characteristics are expected to be determined through survey and observational data. The community characteristics are evaluated in Blocks B and C, which are inputs of Block D. The quality of life assessment, Block B, is used to organize and quantify characteristic data. The outputs of Blocks B and C are used as inputs into the compromise decision support problem (cDSP) in Block D. Energy will be allocated to loads based on the available energy using the cDSP. More information on the general structure of the cDSP can be found in [23]. The solution space from the cDSP is the output of Block D. The solution space is explored using a scenario analysis, in Block E. The solutions are ultimately selected by a decision maker, as represented in Block F. The decision makers may be a social entrepreneur or operation manager. If the solutions are not appropriate, the cDSP can be modified and new options can be generated.

2.1 Block B (Figure 1): Quality of Life Assessment

The quality of life assessment is addressed in [22]. We identify eleven parameters to define quality of life. These parameters include; water, sanitation, healthcare, food, environment quality, safety, education, leisure/social activities, emotional state, physical state, and freedoms. Each of the parameters are considered by their condition, importance to the community, and reliance on energy. For this paper, four parameters are examined. These parameters include water, safety, education, and leisure/social activities. These parameters are selected to demonstrate the

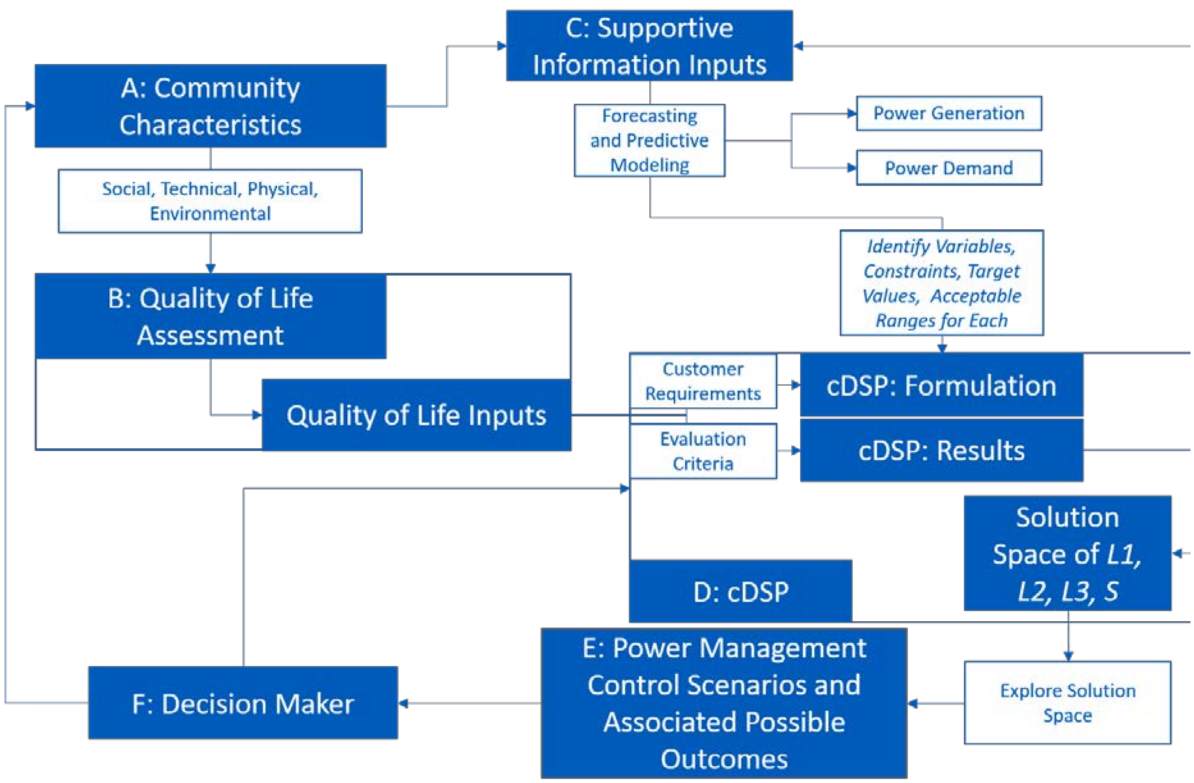

FIGURE 1: PROPOSED FRAMEWORK FOR INTEGRATING QUALITY OF LIFE AND POWER MANAGEMENT

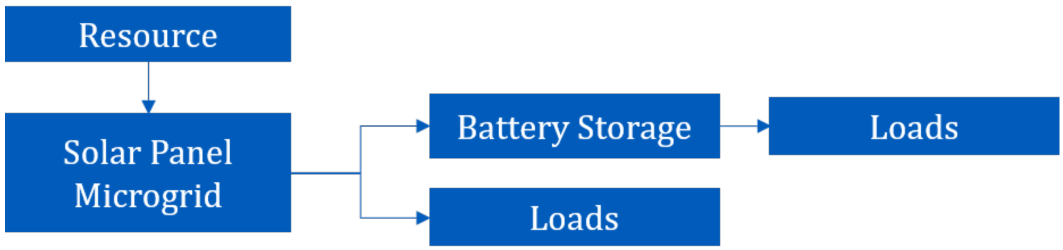

FIGURE 2 : GENERAL CONCEPTUAL MODEL

framework for power management using quality of life. Water encompasses access, transportation, and treatment. Education encompasses the number of students, years of schooling, equality, and teacher to student ratios. Leisure/social activities consist of community organized events, personal relationships, and free time. This is based on the literature of the social development indices [10-14]. Any set of quality of life parameters could be used. In exploring the areas where quality of life could be improved, decisions can be made within the limitations of the constraints. By understanding the areas where energy can effectively improve quality of life, the system requirements are developed.

2.2 Blocks D, E, and F (Figure 1): cDSP for Power Management

Developing operational procedures that are aimed at uplifting quality of life can be accomplished through prioritizing loads. Prioritization should be based on characteristics of a community. Balancing the loads that provide the greatest positive impact for a community can support well-being. The flow of energy through the microgrid system is depicted in Figure 2. It is assumed this system can also power loads using stored energy. The conceptual understanding of the system is needed in formulating the cDSP.

2.2.1 D: Overview of the Compromise Decision Support Problem

The cDSP is a hybrid between mathematical and goal programming used to find satisficing solutions [23]. In this approach, we develop a set of goals to be met for system operation. These goals are based on given information for the system, to find the variables that satisfy the system requirements. The problem is bounded by the constraints of the system. In this paper, the cDSP is used for energy resource allocation for a microgrid in a developing community. The cDSP is formulated by identifying system variables, constraints, and goals. The cDSP is organized by four categories; given, find, satisfy, and minimize. The goals conflict, and require a set of solutions to achieve the best outcomes. These solutions are not optimal, but satisficing. The solution set is representative of the trade-offs of meeting each of the goals. The variables are found by satisfying the goals, constraints, and bounds. Using the cDSP, the deviations for the target values for each of the goals of the system are minimized. The specifics of this process are available in [23]. The cDSP is commonly used in design [23]. However, this approach can be used for system operation. The solutions from the cDSP are energy allocations for each load. In this section, we will demonstrate the framework that incorporates quality of life in power management decision making.

2.2.2 D, E, and F: Application of the cDSP and Scenario Planning

The cDSP is exercised for the control of the rural microgrid. The general formulation for the energy resource allocation is presented in this section. The objective is for the physical system to meet the daily demand. Beyond this, the objective is to uplift the community. By consistently meeting the energy demanded, it is inferred the associated positive impacts improve community conditions. When the available energy is insufficient, these positive impacts are hindered. Reducing the repercussions from a limited supply is needed. Pairing quality of life with the cDSP mathematically incorporates these considerations. The solutions from the cDSP correspond to energy load allocations based on the production and consumption. The demand is represented by specific energy loads in the cDSP. In the cDSP, the goal for each load is to meet the target value.

For our cDSP we first identify the end requirements. The objective is to reach the target value demanded for each load. These requirements are formed with the intention of maximizing the positive societal impact, or minimizing the practices impeded by limited access to electricity. The goals are derived from the quality of life model, Block B. The end requirements are formatted as goals in the cDSP as in Equation 1.

$$\frac{P_i t_{it}}{PT_{it}} + d_i^- - d_i^+ = 1 \quad (1)$$

where P is the power, i is the number of loads, and t is the time period. In Equation 1, the numerator of the first term is the variable load, and the denominator is the target value of the variable. The deviation variables, d_i^+ and d_i^-, represent the distance between the variable and target value of the variable. Equation 1 is applied to each load and each time period.

The variables in this problem are the energy for each load, and the amount of energy supplied for the battery storage. Each of the loads has a target value for a specific time period. The difference between the target and variable values is the deviation variable. Minimizing the sum of the deviation variables is the overall objective function in this problem as in Equation 2. Two deviation variables exist; for underachievement of the goal, or overachievement of the goal [23]. If one exists, the other should be a value of zero. The variables and deviation variables are described as listed.

Variables

P_{it}: Power demand for the load

S_{it}: Energy storage

Deviation Variables

d_i^- : Underachievement

d_i^+: Overachievement

$$D = \sum_{i=1}^{n} W_i * (d_i^- + d_i^+) \; ; \; \sum_{i=1}^{n} W_i = 1 \quad (2)$$

In Equation 2, W refers to the weight applied to the deviation variable. The cDSP is exercised for different design scenarios. This is achieved with different weighting combinations of each variable to create a solution space.

Basic information is needed on the generation, demand, and system specifications. Energy production depends on the type of resource, the location and weather patterns of the community, and the system capacity. Energy dispatched for the loads cannot exceed the amount produced. The energy demand or anticipated demand is necessary in formulating the target values for each of the goals. The microgrid system specifications are represented using the constraints and bounds of the problem. The relationships between the demand, generation, and storage are defined in constraint Equation 3. The conflicts between the goals are also related using this equation. Power allocated to one load cannot be allocated to another. System losses will not be considered in this analysis. Therefore, it is assumed the available energy has already accounted for the losses.

$$St{+}1 = St + Pgtgt - P1t1t - P2t2t - P3t3t\ldots - Pntnt \quad (3)$$

In Equation 3, S_t is the current energy in storage, $P_g t_{gt}$ is the energy generated, and the remaining terms, $P_{1:n} t_{1:n}$, represent the energy demanded by each load. The constraint equation represents the relationship between the supply, and the energy demanded. This equation is an equality constraint as the supplied energy cannot exceed the available energy. In this formulation, the energy available does not include system losses. The boundaries of the system are determined through the supportive information, represented as Block C. The list below describes the boundaries for each variable.

Boundaries

$Pt_i \geq 0$: The energy demand is assumed to be greater or equal to 0

$S \geq 0$: The system storage is assumed to be greater or equal to 0

$S \leq SystemCapacity$: The storage cannot exceed the capacity of the battery

$d_i \geq 0$: The deviation variables must be greater or equal to 0

$d^-_i * d^+_i = 0$: The deviation variable must multiply to 0 such that one variable has a value of 0

The constraints and boundaries defined in the cDSP are consistent with the assumed system. The results of the cDSP are a set of solutions based on weighting the variables within the deviation function differently. We represent the solution space using ternary plots. As mentioned previously, the weights are applied to each of the deviation variables in the minimization equation. And, each deviation variable corresponds to a system variable. Using the ternary plots, we can see the solutions for each variable with respect to each of the weighting combinations used in the cDSP. From this space, we can select solutions appropriately. A limitation of this approach is only three variables can be used. This can restrict how the problem is structured. A key feature of the formulation is the flexibility to adapt to different conditions. Adaptability is important for daily, weekly, and monthly planning. This is also crucial for the application of the method for different communities. The formulation can be changed to include additional generation, demand, or storage components. This flexibility allows for appropriate representation of the system.

The cDSP allows us to develop a solution spaces for allocating available energy. We can explore solutions given different requirements. Having a set of solutions is especially effective in these types of problems where the operation requirements vary. We demonstrate how solutions change based on community's needs through scenario planning. The requirements are developed using the quality of life model. The possible scenarios are matched to the most appropriate solution based on the prioritization of the energy demand. Within these scenarios, there is additional flexibility of the solutions. The framework is developed to integrate quality of life and power management to support decision making.

3 RESULTS AND DISCUSSION

In this section, we demonstrate the function of the framework through an applied problem. Using the example problem, we illustrate how quality of life considerations are integrated in power management. The solution space developed using the framework supports organizations engaged in sustainable development. SunMoksha has provided the data used in this paper [24].

3.1 Block B (Figure 1): Quality of Life

An example village is used in demonstrating the framework. The existing and required energy related resources and devices are described in Table 1. In this paper, four parameters contributing to quality of life are examined. However, decision makers can choose the parameters most appropriate for the community. The resources are related to the quality of life parameter to identify possible impacts. The characteristics of the community provide insight into the importance of the parameter and the reliance on electricity. Each parameter that contributes to quality of life is reliant on a multitude of factors. In microgrid power management, the focus is on how access to electricity supports fulfilling the parameter.

For an example community, fulfilling the water and safety needs may have a greater reliance on electricity. Therefore, these factors should be prioritized in the formation of design requirements. In this example, we assume system requirements should prioritize water and safety. The information from the quality of life analysis is used as inputs for the cDSP.

TABLE 1 : EXAMPLE 1 CHARACTERISTICS [24]

Parameter	Existing Resources	Required Resources
Water	Wells	Pump system
Safety	Data Unavailable	Multiple lights per home, Streetlights powered longer
Education	Data Unavailable	Data Unavailable
Leisure/Social	Data Unavailable	Data Unavailable

3.2 Block D (Figure 1): cDSP for Power Management

In this paper, we examine four quality of life parameters. We consider the power loads for water pumps, streetlights, and households. Loads for pumping water are related to fulfilling the water parameter. Streetlights represent the safety parameter. Household energy corresponds to the education and leisure parameters. This is based on information from SunMoksha [24] and the World Bank [25]. The World Bank identifies impacts related to powering devices [25]. Other loads may support these same parameters. However, for simplification, we focus on the aforementioned loads. Additionally, other factors contribute to quality of life and the fulfillment of these parameters. For the purpose of this analysis, we are only focusing on the relationships between quality of life and the power load. From the quality of life model, water and safety are high priority. This is the basis for the cDSP goals. In the computation of the cDSP, weights are assigned to each of the goals to form the solution space. A solution for each goal can be inferred from the quality of life model results. When power production exceeds demand, the batteries are charged. The stored energy is used later when the demand is greater than production.

The data used in this paper is provided by SunMoksha [24]. We assume two lightbulbs, one television, one fan, and one mobile charger per household are used for six hours per day in the evening, for 80 houses. For the entire community, three water pumps would be used for six hours per day, during the day, and streetlights would be powered for

12 hours in the evening. We observe that demand changes day to day and seasonally, as well as increase over time. For example, a fan may need to be used on a warm day but not on a cold day. This baseline demand is used for this analysis. The available energy of the system is estimated to be 40 kWh/day. This is based on solar insolation and solar panel data. Assumptions are made for the system losses. The intermittency of the renewable solar source will also cause variations in energy generation. For this analysis, the generation will be kept constant for simplification.

The power production and consumption are examined over 24 hours. The production and consumption are assumed to be constant for each hour interval. For each load, the times of use are fixed. Two time periods are analyzed. The first time period is called ”Daytime,” and refers to the hours between 6am to 6pm. The second time period is called ”Nighttime,” and corresponds to the hours between 6pm and 6am. In the Daytime period, there is both power production and consumption. The Nighttime period has only demand. The battery is a load in the Daytime period and a source in the Nighttime period. The application of the cDSP and the flexibility of the formulation are demonstrated through two test problems. The cDSP formulation for the test problem is summarized in Table 2. The energy demand for each load is the target value for the respective goal. The loads are determined through the quality of life analysis. The variables and boundary conditions are determined by the system specifications. The constraints for the cDSP relate the energy production, consumption, and the battery storage. The objective of the cDSP formulation is to minimize the deviation between the calculated variable and target values. Assigning different weighting combinations to the deviation variables for each of the goals creates the sets of solutions. The weighting combinations correspond to the priority in which power is distributed to the loads. The desired prioritization is based on the community’s needs and perspectives. The needs and perspectives are defined using the quality of life model.

The cDSP for power management is computed using the computing infrastructure DSIDES Decision Support in the Design of Engineering Systems. The results of the cDSP are values for each of the variables. In the microgrid, the values of the variables correspond to the allocation of power for each load/battery, for each time period.

TABLE 2 : cDSP TEST PROBLEM FORMULATION

Given	Maximize the energy demand met
Find	**System Variables** S_t $L_{1t} = Pt_1$: Load 1 (Water) $L_{2t} = Pt_2$: Load 2 (Safety) $L_{3t} = Pt_3$: Load 3 (Household) **Deviation Variables** $d_i^-, d_i^+ = 1{:}3$
Satisfy	**System Goals** $\frac{P_1 t_{1t}}{PT_{1t}} + d_1^- - d_1^+ = 1$ (1.1) $\frac{P_2 t_{2t}}{PT_{2t}} + d_2^- - d_2^+ = 1$ (1.2) $\frac{P_3 t_{3t}}{PT_{3t}} + d_3^- - d_3^+ = 1$ (1.3) **System Constraints** $St+1 = St + Pgtgt - P1t1t - P2t2t - P3t3t$ (3.1) **System Bounds** $Pt_i \geq 0$ $S \geq 0$ $S \leq SystemCapacity$ $d_i \geq 0$, $d_i^- * d_i^+ = 0$
Minimize	**Deviation Function** $D = \sum_{i=1}^{n} W_i * (d_i^- + d_i^+)$; $\sum_{i=1}^{n} W_i = 1$ (2.1)

3.3 Blocks C, D, and E (Figure 1): Test Problem

The cDSP is applied to a test problem to validate the model. The test problem demonstrates how the cDSP is used for resource allocation through two scenarios. In these two scenarios, the system conditions remain constant, while the target values for the goals vary. In the first scenario, the power is assumed for three water pumps for six hours, 12 streetlights for 12 hours, and 70 homes for six hours. In the second scenario, the demand is assumed to be half of that in the first scenario.

The function of the model for power management is demonstrated through Scenario 1. The flexibility of the model is illustrated using Scenario 2. This is achieved by examining how changes to the solution space impacts power management. The combination of these cases allows us to understand what is needed to sufficiently meet the needs of a community. The results of the test problem support the validity of the method. The target values for Scenario 1 are summarized in Table 3.

TABLE 3 : SCENARIO 1 TARGET VALUES

cDSP Parameter	Energy (kWh)
Water Energy Target Value	45.0
Safety Energy Target Value	2.0
Household Energy Target Value	70.0
Available Energy	40.0

The water demand load is shown in Figure 3. We present the results from the cDSP using a ternary plot. The ternary plots are generated using a code by Ulrich Theune in Matlab [26, 27]. Energy allocation for different combinations of weights is shown in the plot. The ternary plot allows us to visualize feasible solution regions. Each ternary plot is for one of the variables used in the cDSP. The cDSP is exercised for the design scenarios. This is achieved by applying different weights to each of the variables. The impact of changing the weights of each of the variables is then visually represented using the ternary plot. In determining solutions that prioritize one variable over another, this is especially useful.

The line depicted on the plot and the key provides a boundary where the desired solutions lie. The target value of the demand exceeds the supply. Thus, the goal becomes to meet as much of the demand as possible. The ternary plot for the streetlight load is shown in Figure 4. This load is indicative of the safety parameter in the quality of life framework.

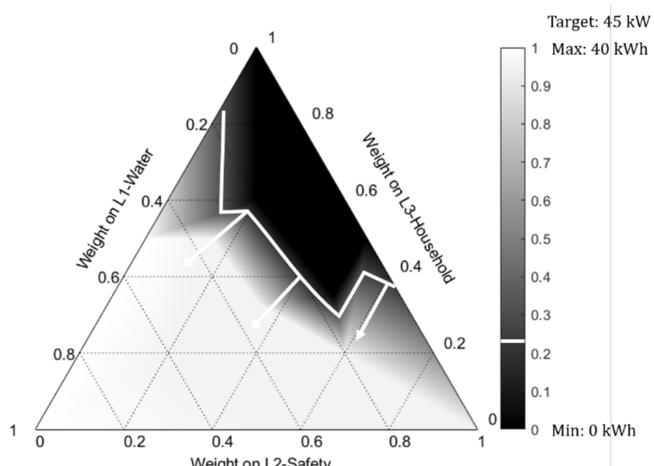

FIGURE 3 : TERNARY PLOT SCENARIO 1- WATER

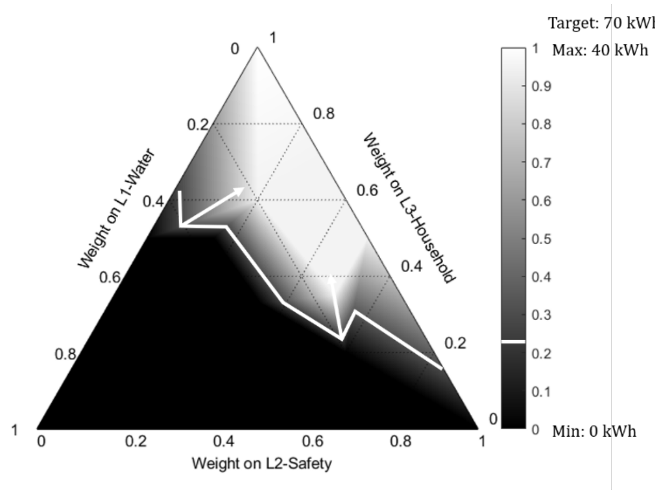

FIGURE 4 : TERNARY PLOT SCENARIO 1- SAFETY

The region where this goal can be met is much larger than that of the other variable loads (water and household). The likely cause is the relatively small target value of this load. Figure 5 is the ternary plot for the household energy. This corresponds to the education and leisure parameters in the quality of life model.

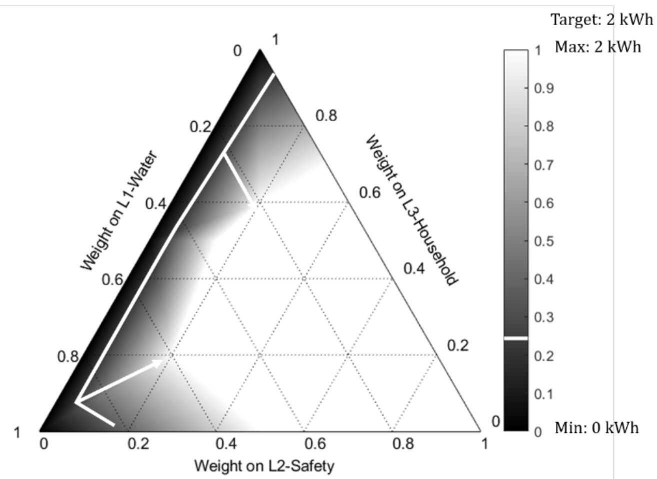

FIGURE 5 : TERNARY PLOT SCENARIO 1- HOUSEHOLD DEMAND

The ternary plots allow us to visually understand the regions of feasibility and the corresponding weighting combinations of all of the variables. Combining the ternary plots shows the overlap of the feasible regions. Plotting these regions for each of the variables on the same ternary plot is represented in Figure 6. Similar to the individual ternary plots, the results of changing the applied weighting to each of the variables is illustrated in the combined ternary plot.

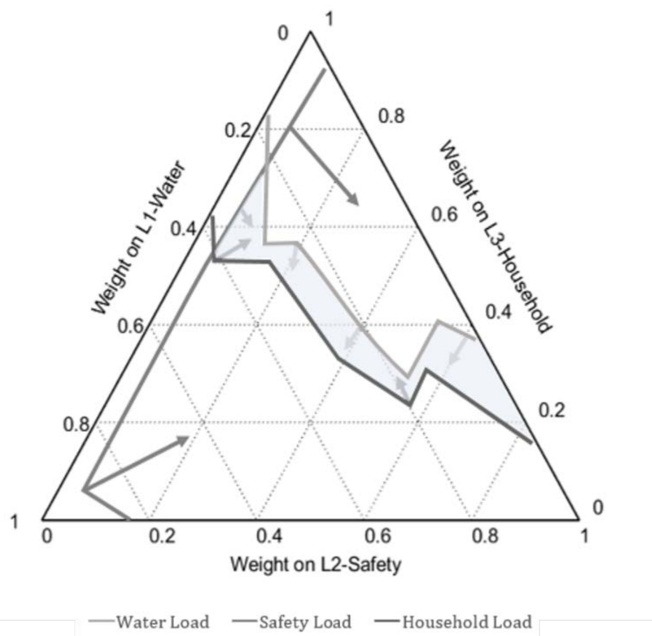

FIGURE 6 : COMBINED TERNARY PLOT SCENARIO 1

In Figure 6, the combined region shows the part of the solution space that would balance the three variables. In the system this indicates some energy would be allocated to each of the loads. Within this combined region, many satisficing solutions exist. These solutions correspond to how the variables are weighted. Based on what the community needs, the selected solutions can be changed. All of the loads may be needed but have different priority. For example, the water load could require priority. In this case, the solution that has a higher weight on the water variable would be selected. The weights applied on the other two variables are non-zero and within the combined region. However, depending on the community requirements, there may be times in which meeting all of the goals is not necessary. Therefore, solutions may lie outside of the combined region. For example, if household energy is needed, the solution selected would correspond with a higher weight applied to the household variable. It is possible the other loads are not needed. Thus, the corresponding weights of the other loads are minimal or zero. Therefore, solutions above the defined line and outside of the combined region would be acceptable. However, this may imply an existing power management restriction or demand-side management. This could also occur in the event appliances or devices are not required during a given time period. Within and beyond the combined space, multiple solutions exist. Based on the quality of life needs at a given time, a solution can be selected. In this scenario, the target values for the water and household loads are assumed to be higher than the available energy. Therefore, the assumption is that the target values cannot be met for those loads. The objective becomes to meet as much the target values as possible. Limiting the hours of consumption or supplying energy to only one or two loads could be the microgrid response. This would be to ensure the energy has the greatest impact on quality of life.

We observe more power is allocated to the loads that have a higher applied weight. The selected satisficing solution has a weighting combination that aligns with the prioritization of the loads. The scenario analysis provides insight as to what solutions should be chosen given the community's status. These needs will change and the flexibility of the framework allows for this essential adaptability of the microgrid. If a solution space does not exist, the requirements can be redefined. Additionally, if the solution space is too restricted, or not appropriate for the community, the social entrepreneur can redefine the requirements. A second scenario is presented to illustrate changing the requirements for the same formulation yields a different solution space.

Scenario 2 is formulated similarly to Scenario 1, except for the target goal values. In this scenario, the target goal values are half of those in Scenario 1. Reducing the goals for each of the variables is expected to increase the solution space given the same available energy resource. The variables are the energy allocated for pumping water, powering streetlights, and household loads. Again, these variables are related to the quality of life model parameters. These parameters specifically are water, safety, education, and leisure. The analysis of this scenario is also helpful in developing a range of power management plans. The options for the microgrid demonstrates the flexibility of the satisficing solution space. Furthermore, this method may be adapted to different communities, and to the changes that occur within a community over time. The target values for Scenario 2 are outlined in Table 4.

TABLE 4 : SCENARIO 2 TARGET VALUES

cDSP Parameter	Energy (kWh)
Water Energy Target Value	23.0
Safety Energy Target Value	1.0
Household Energy Target Value	35.0
Available Energy	40.0

In Scenario 1, the target water load exceeds the produced energy. In Scenario 2, the target value is less than the available energy. If only one pump needs to be powered, the reduced target may be ideal. However, the total demand still exceeds the energy produced. Therefore, the goals again are to meet as much of the target values as possible. Proportionally, the safety load is much smaller than that of the water and household loads. For quality of life, this parameter may be easier to satisfy. This is also reflected by the solution space of the ternary plot. Half of the household load (compared to Scenario 1) is still close to the available energy. This implies the supply may continue to be insufficient. This would warrant upgrades to the microgrid.

Modifying the requirements within the cDSP changes the solution space and the energy allocation. The combined ternary plot for Scenario 2 is shown in Figure 7. With the assumption the demand exceeds the supply, decisions are required in allocating the available energy. Within the combined region, each of the quality of life parameters are partially satisfied. In some instances, the solutions may lie outside of this region. This is acceptable if only one or two loads need to be met. For example, if only the household energy needs to be met, any solution above that variable's threshold line is satisfactory. Again, this could be for a multitude of reasons. The solution space allows us to select different options based on the specific needs at a given time. Furthermore, having a set of solutions provides the flexibility necessary in an adaptable system.

The combined region of Scenario 2 is larger than that of Scenario 1. This is because the target values for each of the variables have been reduced. The analysis of the test problem provides insight on power management by changing the solution space. This test problem allows us to consider the outcomes of only meeting half of the total demand. In the system, this may mean reduced hours of consumption. The test

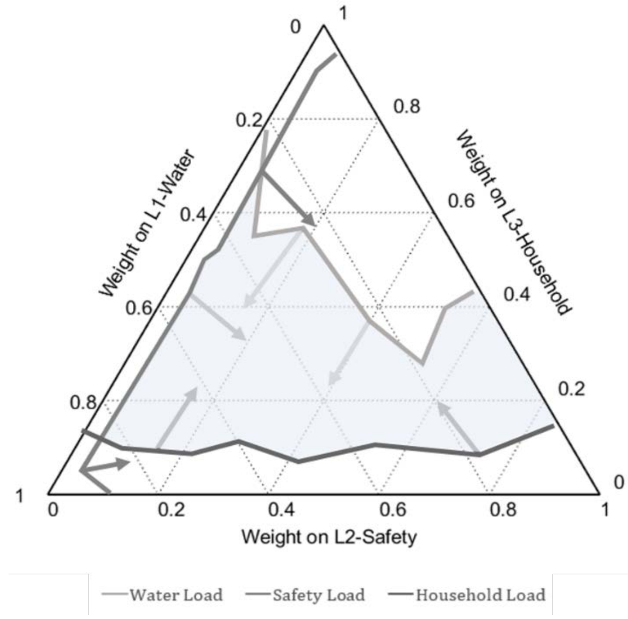

FIGURE 7 : COMBINED TERNARY PLOT SCENARIO 2

problem allows us to explore alternative solutions and realize the impact of varying the energy supplied. Social entrepreneurs can select solutions from either space depending on changes in requirements.

Comparing the results from the cDSP, we can assess which solution may be most fitting at a given time. This comparison provides valuable insight into the flexible structure of the solution space. Scenario planning is used to anticipate possible events that may arise and match those to solutions from the cDSP.

In the test problem presented, power management procedures can be implemented to mitigate the impact of limited power availability. Providing power to different loads and replenishing the storage can be conflicting objectives. Exploring the potential solutions from the cDSP provides insight into how power management guidelines can be implemented. The cDSP allows us to examine the solution space for control strategies. Pairing the cDSP with the quality of life model can support the preferred areas of impact based on the community perspectives. These community perspectives are crucial in defining the requirements of the system, as well as prioritizing the resource allocations. Power management could include limiting hours of use or available power and allocating power to specific loads. To illustrate the application of the quality of life model, power

TABLE 5 : POWER MANAGEMENT SCENARIOS

Load Priority	Water Load (kWh)	Safety Load (kWh)	Household Load (kWh)	Storage (kWh)
Water and Safety Priority	38.0	2.0	0.0	2.0
Household Priority	0.0	0.0	40.0	40.0
Household and Safety Priority	0.0	2.0	38.0	40.0
All priority	23.0	1.0	16.0	17.0

management is discussed in the context of powering specific loads.

Every solution from the cDSP provides quantitative values for each of the loads and battery storage for each time period. Using scenario planning, we can anticipate which solutions may be appropriate for different conditions. Scenarios are developed by exploring possible outcomes and relating those to the power management model. These scenarios are presented using the variables in the cDSP in Table 5. The scenarios selected correspond to the prioritization of the three loads. The scenario where water and safety are prioritized was selected based on the quality of life model. The remaining scenarios are chosen to demonstrate the change in energy allocation based on the load prioritization. Other scenarios exist however, this set is compiled to illustrate how the results of the cDSP will change accordingly to the needed load(s).

The solutions from the cDSP are mapped to possible situations in Table 5. These solutions are derived from the ternary plots from the test problem. Examining the results and associated scenarios allows us to develop the outline for a power management plan. Therefore, if the condition of the community is presented and water and safety need to be prioritized, the energy is allocated to water and safety. Similarly, if the household demand is most needed, the available resources are allocated solely to that load. If all of the loads are of importance, the available energy is allocated to minimize the difference between the targeted demand and variable value. This power management strategy allows for the flexibility to accommodate different types of events and provide possible solutions. Therefore, once we connect the scenario to the solutions, we can refine the chosen solutions to select the one best fitting for the remaining load(s) that are not of the higher priority. By mapping anticipated scenarios to solutions within the solution space, the operation of the microgrid is expected to have an improvement in supporting quality of life or preventing hindrances associated with insufficient available resources. Connecting the solutions from the cDSP to the possible scenarios suggests the results can be utilized in decision making for power management. In Table 5, the scenario solutions are related to the expected impact on the quality of life parameter(s). The impacts that are most helpful to the community will vary. Allocating energy to safety, water, or household demand is more than just powering lights, fans, and pumps. Ensuring these devices and appliances are powered provides better living conditions. Changes in daily life can be empowering for a community. This empowerment is critical in uplifting a community.

Combining quality of life and microgrid operation allows us to provide solutions that are sustainable and resilient. Technical interventions can have a substantial impact, but only if that system continues to uplift and empower the community. Therefore, we must continue to work towards solving problems that inhibit progress and empowerment.

4 CLOSING REMARKS

In this paper, we propose a framework for power management that incorporates quality of life. We connect these domains to promote sustained development. From the quality of life analysis, we gain insight to the community's needs and wants. This information helps to define the requirements for energy allocation. We recognize relationships between the quality of life and the system operation are needed in solutions that support sustainable development. The efficacy of the framework is demonstrated through a test problem. Using different scenarios, we observe the flexibility of the framework in the application. In the example problem, water and safety parameters require prioritization. The solutions from the cDSP reflect these requirements. Within the solution space, additional options exist prioritizing the other load combinations. Decision makers can evaluate and select solutions that are fitting to the needs of the community at a given time. Additionally, the decision makers can change the requirements to restrict or expand the solution space. This flexibility is necessary such that the solutions evolve alongside the community.

Future work will be focused on managing uncertainty, incorporating additional resources in resource allocation, and modeling quality of life interactions using system dynamics. The production and consumption of energy are sources of uncertainty in this problem. In part, consumption can vary for loads that are dependent on resources beyond electricity. Therefore, incorporating robust concepts in the framework is needed. Additionally, modeling changes and correlations in the community is needed to better anticipate operation and design requirements. We remain dedicated to uplifting communities through sustainable development.

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