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Socio-Technical Modeling to Manage Power Distribution for Microgrid Systems With Limited Production Capacity

The quality of life (QOL) in rural communities is improved through electrification. Microgrids can provide electricity in areas where grid access to electricity is infeasible. Still, insufficient power capacity hinders the very progress that microgrids promote. Therefore, we propose a decision-making framework to manage power distribution based on its impact on the rural QOL. Parameters are examined in this paper to represent the QOL pertaining to water, safety, education, and leisure/social activities. Each parameter is evaluated based on condition, community importance, and energy dependence. A solution for power allocation is developed by executing the compromise decision support problem (cDSP) and exploring the solution space. Energy loads, such as those required for powering water pumps, streetlamps, and household devices, are prioritized in the context of the QOL. The technique also allows decision-makers to update the power distribution scheme as the dynamics between energy production and demand change over time. In this paper, we propose a framework for connecting QOL and power management. The flexibility of the approach is demonstrated using a problem with varying scenarios that may be time dependent. The work enables sustainable energy solutions that can evolve with community development. [DOI: 10.1115/1.4052328]

Keywords: *energy, renewable, simulation, solar, system*

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1. Introduction

Rural electrification can positively impact the progress of developing communities. The impact is realized through various aspects including education, health, agriculture, and safety, and results in overall improved quality of life (QOL) [1]. In some rural communities, grid access is limited or costly to implement [2]. In these instances, microgrid systems can be useful. Microgrids operate as stand-alone systems that provide power in rural communities. SunMoksha Power, Pvt. Ltd. is an organization founded by a social entrepreneur, with the goal of sustainable solutions for rural development. The authors are collaborating with this organization as part of our study. SunMoksha has implemented smart microgrid systems in off-grid communities in India. Through these activities, the co-authors from SunMoksha have experienced the problems that exist with stand-alone microgrids in rural development. One significant problem is due to the fixed capacity of microgrid systems. The reliance on renewable resources, such as sunlight, further restricts the supply [3]. Rural microgrids generally have a battery bank to store excess energy for use when the resource is not available. At some point during the life of the microgrid, the limited power capacity of the microgrid can become a reoccurring problem. The problem occurs anytime the level of energy demand becomes greater than that which can be supplied by the system. This takes place in rural communities due to the increased demand for energy that comes with development. Eventually, the disruptive nature of the power can undue much of the social progress that the microgrid enabled. Thus, we present a technique to allocate energy among electrical loads when there is a shortage in the available supply. Our objective is to make these decisions in a manner that is supportive of the rural quality of life.

For the smart microgrid, it becomes possible to control the delivery of power to specific loads. There can be individual circuits for community water pumps, security lights, and individual dwellings. Energy management is also facilitated through the identification of end-use appliances. Combining these identities with the smart

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microgrid could allow power management at the appliance level and is part of ongoing work. Given these capabilities, it is possible to manage the limited power supply in rural settings. Still, there is a lack of understanding about making decisions pertaining to power management. An approach to this could be by setting priorities for power loads that support the well-being of the community. It could be very useful to reserve energy for critical needs, such as purifying water or keeping security lights on at night. However, there are other priorities as well. The authors, with the help of SunMoksha, are creating a framework to incorporate these considerations into the decision-making process. Making these decisions effectively requires an understanding of the relationship energy has with the rural quality of life. Lloyd et al. examine social elevation and discuss how electrification reduces health hazards and the burden of household activities [4]. Sovacool emphasizes the impact energy has on poverty, pollution, health, gender equality, and education [5]. Incorporating social considerations into the analysis is crucial in providing sustainable solutions to empower people. The positive impact of electrification on education and poverty alleviation is affirmed in Refs. [6,7]. Mahajan et al. discuss the behavioral impact of access to lighting [8]. From these studies, we recognize access to electricity can be transformative for well-being. However, solutions that focus on sustaining well-being over the life of microgrids are not adequately addressed.

Well-being is frequently assessed by the level of needs satisfied. Maslow's *Hierarchy of Needs* [9] and Max-Neef's *Fundamental Human Needs* [10] are two common methods for defining needs. Maslow defines a hierarchy of needs that ranges from basic to complex. Before high-level needs are satisfied, low-level needs require fulfillment. However, as technology advances, this hierarchy of needs does not necessarily convey. For example, there may be cases where education is accessible, but clean water is not. Max-Neef defines fundamental human needs without a hierarchy. These fundamental needs include subsistence, protection, affection, understanding, participation, leisure, creation, identity, and freedom. Moreover, both Maslow and Max-Neef define basic needs and support an understanding of QOL. Costanza et al. examine the connections between QOL, well-being, and human needs [11]. Weighting, summation, and multiplicative relationships are approaches highlighted for QOL assessment. Additionally, many methods exist to rank social well-being to understand and compare the level to which needs are met and the associated level of development. The *Human Development Index* [12], *Multidimensional Poverty Index* [12], *Social Process Index* [13], *Eurostat Quality of Life* [14], *World Happiness Report* [15], *and Bhutan's Gross National Happiness Index* [16] are all methods for ranking nations based on well-being indicators. However, in these methods, the ranking is relative to other countries. Moreover, these approaches do not adequately portray the needs of a specific community within a country. This is notable since the development of a country and the extent of that development taking place within a given community may be quite different. Assessments of well-being can be conducted at the community level and represented in the requirements for microgrid design and operation. There is a need to consider the interactions between the technology, society, and economy when solving these complex problems [17]. Principles for socio-technical design and design in the developing world are discussed in Refs. [18,19]. One of the themes of these studies is the necessity of understanding the setting and conditions. Yadav et al. suggest the formation of tensions through dilemmas between social, environmental, and economic considerations [20,21]. Nonetheless, more work is required to adequately incorporate social considerations in technical systems [22]. Socio-technical models are a valuable means through which these relationships can be explored and refined for use in computer-based exploration.

Socio-technical applications have been demonstrated within community development and energy systems. Baek et al. examine a framework for community resilience and the formation of objectives for socio-technical design [23]. This type of approach is imperative in creating solutions that sustain development. A study by Akinyele discussed challenges for solar power systems in developing regions. The authors point out the significance of social dynamics in determining demand and design requirements for energy systems [24]. Zhuang et al. discuss decision-making with varying preferences [25]. When setting priorities for energy loads, it is important to understand the impact each has on well-being. Any technique for setting these priorities must also be adaptable to changes in demand that occur over time. Elavarasan discusses the barriers to renewable energy in India [22]. While some barriers are technical, others are non-technical. In a study by Palma-Behnke et al., power management is approached by supporting specific demands associated with water and electricity, while minimizing cost [26]. The work stresses the importance of managing the limited energy supply in a manner that sustains development. This is promoted by allocating power to those electrical devices that support the rural QOL most effectively. Both technical and non-technical factors are needed in modeling and decision-making. A socio-technical model is very useful for exploring the relationship between energy use and the rural quality of life. Examining this relationship through modeling scenarios also promotes sustainable power management solutions.

Table 1 categorizes the relevant literature as it relates to rural electrification and sustainable development. The benefits electrification has on social well-being in rural development are well recognized [4–8]. This impact has also been observed by the co-authors at SunMoksha. A power management technique is needed to prioritize loads when the demand is greater than the limited supply [23–25]. It is appropriate that decision-based management be supportive of social well-being [20–26]. While the information to support this approach can be complex and challenging to incorporate in analysis, it is vital to sustainable development. Considerations of non-technical factors are needed in managing available resources. Based on this understanding of the literature, we hypothesize that decision-based power management can be performed using the relationship between rural well-being and energy use. In this specific work, we will lay the groundwork to test this idea. Our framework allows QOL to be incorporated into the decision-making process. An important feature of this framework is adaptivity, which is important as more information about the relationship is learned. The literature shows that community QOL and resource allocation connected, but the connection is not adequately understood or integrated. There are challenges in representing the non-technical factors in microgrid operation. Integrating QOL in technical systems is difficult because the information is qualitative. We identify the challenges as the ability to characterize the QOL,

Table 1 Literature review summary

Research topic	Paper	Define development	Assess development	Community specific	Application to energy systems	Power management
Energy in developing communities	[1–8]	✓			✓	
Well-being indicators	[9–16]	✓	✓			
Socio-technical applications	[17–22,25,26]			✓	✓	✓
Power management practices	[22,25,26]					✓

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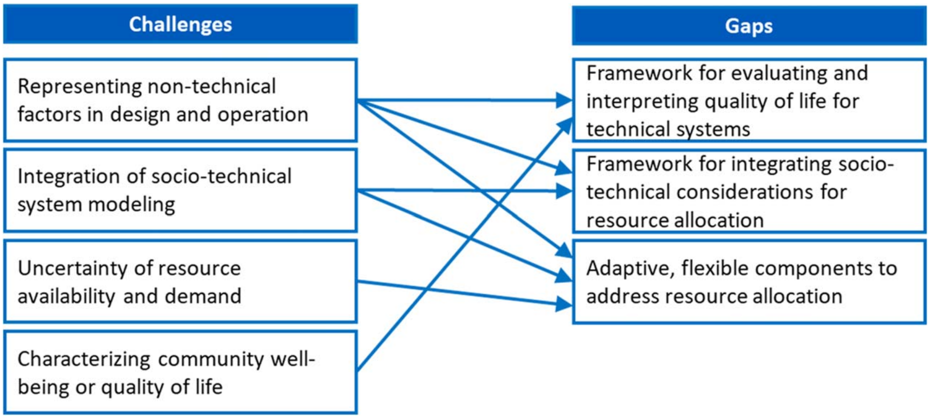

Fig. 1 Challenges and gaps in the establishment of the socio-technical relationship

represent non-technical factors, integrate these non-technical factors, and manage uncertainty. These challenges are summarized in Fig. 1. The existing work also provides suggestions for pairing social and technical considerations that can provide appropriate solutions.

We propose a framework with flexible components to represent the relationship between the social and technical domains. Salient features of the framework are the socio-technical model, decision-based support, and a mathematical basis to interpret the QOL. Concepts of well-being in Refs. [9–16] are used to devise a QOL model for microgrid operation. This approach provides a first step in identifying socio-technical model parameters that can be related to energy use. The flexibility of this framework allows it to incorporate new information about the complex socio-technical relationship. Thus, the performance of this model can be expected to improve over time. This adaptive capability captures changes in the socio-technical relationship that occur over time. Adaptability is also critical in overcoming challenges related to the interpretation of qualitative information and mitigation of uncertainty of the socio-technical relationship.

The functionality and adaptability of the proposed framework are examined through two test problems in the presented work. The problems demonstrate the use of this framework in resolving the limited amount of power between three power loads. This approach is validated using the Validation Square [27]. Detailed information about the use of this method in this application can be found in Ref. [28]. Using this construct, the logical consistency, appropriateness of the example problem, the ability to provide utility, and application to comprehensive problems are addressed, respectively [29]. The method provides a systematic approach to verification and validation for design research, where quantitative validation may not be appropriate. Our collaboration with SunMoksha enables the validation and verification of this framework. The presented approach is also a component of a larger framework anchored in integrating qualitative and quantitative information in the analysis of the social, technical, economic, and environmental dynamics of a system. The framework supports the expansion of socio-technical considerations beyond design to operation of systems. Determining power management solutions that are connected to QOL is an example of how this framework can be used.

2 Framework

This section introduces a framework to support microgrid power management decisions based on community needs. A QOL model is developed to facilitate an understanding of these needs. This model also relates QOL parameters to energy demand. A power management model can then determine energy allocation options. The solution space is developed by pairing these two models as shown in Fig. 2.

Understanding the social, technical, physical, and environmental characteristics of the community corresponds to Block A of Fig. 2. These characteristics will be determined through the use of surveys and other data as can be captured in the community microgrid system. SunMoksha has developed a survey for collecting

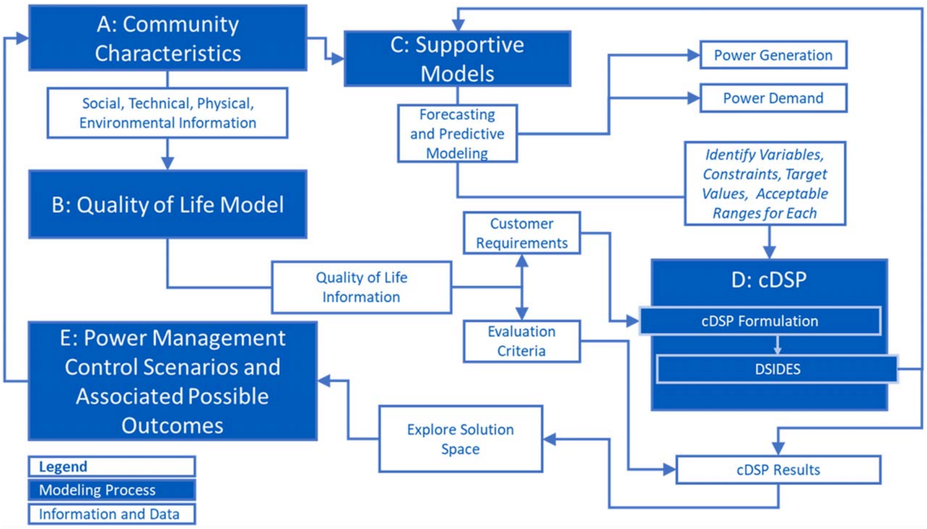

Fig. 2 The proposed framework for integrated QOL and power management

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Table 2 QOL parameter condition descriptions

	Parameter			
Level	Water	Safety	Education	Leisure/social activities
0	No access, transportation, or treatment	No security lights, high crime, violence, threat of wildlife attacks	No education	No leisure or social activities, no personal relationships
1	Access, limited transportation, no treatment, harmful contaminants	No streetlamps, some lights for houses and community buildings, high crime, violence, limited protection from wildlife	Primary education, high student–teacher ratio	Occasional social meetings, limited personal relationships, no designated place to gather, limited to no free time
2	Access, limited transportation and treatment, some harmful contaminants	Streetlamps 25% at night, minimal community and household lighting, moderate crime, violence, some laws, but no enforcement, limited protection from wildlife	Primary and secondary education, high student–teacher ratio	Social meetings, general place to gather, organized regular meetings, personal relationships, limited free time
3	Access, transportation, some treatment, non-harmful contamination	Streetlamps 50% at night, moderate community and household lighting, moderate crime, violence, limited law enforcement, moderate protection from wildlife	Primary and secondary education, low to moderate student–teacher ratio	Community events, activities, place(s) for gathering, limited free time
4	Access, transportation, treatment, no contamination, small-scale treatment and distribution	Streetlamps 75% at night, all community and household lighting, limited crime and violence, law enforcement, protection from wildlife	Primary, secondary, and some tertiary education, low to moderate student–teacher ratio	Organized community events, personal relationships, some economic barriers, free time
5	Access, transportation, large-scale treatment and distribution	Streetlamps 95% at night, all community and household lighting, limited crime and violence, trusted law enforcement, protection from wildlife	Primary, secondary, and tertiary education, moderate student–teacher ratio	Organized community events, options for social engagement, organized community activities, personal relationships, free time

information in each village. Methods for gathering, quantifying, and evaluating information about these characteristics will be studied in other work. Therefore, we assume values exist for Block A. These values are considered in the QOL assessment in Block B. Block C provides characteristics of the microgrid operation and is not part of the current work. Blocks B and C provide energy availability and demand information to the compromise decision support problem (cDSP) in Block D. The cDSP establishes the energy allocations in light of the available energy and demand needs. The approach enables consideration of the QOL based on the unique characteristics of the community. The cDSP is a hybrid between mathematical and goal programming [30]. The solution space from the cDSP is the output of Block D. Exploration occurs through scenario analyses, in Block E. The solutions are ultimately selected by a human decision-maker. The decision-maker could be a social entrepreneur or operation manager. If the solutions are not appropriate, the cDSP can be modified and new options can be generated. These requirements can also be updated as conditions change over time.

2.1 Block B: Quality of Life Assessment. The model developed in this section is used to assess QOL and support design decisions. The assessment of QOL is with respect to energy dependence and the importance of each parameter from the community perspective. The model is based on eleven parameters as presented in Ref. [31]. These parameters include water, sanitation, healthcare, food, environment quality, safety, education, leisure/social activities, emotional state, physical state, and freedoms. Each of the parameters is evaluated with three measurable components. The initial QOL is determined by assessing these eleven parameters. Four of the parameters are examined in this work to demonstrate the proposed technique. These parameters include water, safety, education, and leisure/social activities. Water encompasses access, transportation, and treatment. Education is based on the number of students and level of education and the student–teacher ratio. Safety considers the level of safety from crime, violence, and wildlife attacks. Leisure/social activities consist of community-organized events, personal relationships, and free time.

2.1.1 Condition, Community Importance, and Energy Dependence. Three components of the model include the parameter condition, C, the community importance, CI, and the energy dependence ED [32]. The condition component is used to assess the level of development. The conditions have been defined through literature analysis. These ratings can be refined over time and expanded to encompass additional considerations. The community importance component is used to represent the perspectives and priorities of the community members with respect to each parameter. Energy dependence relates the parameters to the associated energy demand by electrical devices. Both community importance and energy dependence can be compared to the existing condition to identify the need for energy for the given QOL parameter.

The condition component represents the status or fulfillment of each QOL parameter. The condition is characterized using survey and observational data. Given this characterization, the condition of the QOL parameters is assigned a corresponding numeric level. A condition of 0 indicates low satisfaction while a condition of 5 indicates high satisfaction. The condition descriptions in Table 2 are developed from Refs. [33–40].

In the system design process, community values need representation. Additionally, the QOL indicators need to be mapped to energy. The importance and dependence components point to the areas of greatest possible impact. The importance component is used to incorporate the priorities of the parameter to the community. Including these priorities not only is one step forward in empowerment but also supports better system design. Equation (1) represents the relationship between the importance and level

$$\mathrm{CI}(i) = \frac{5 - C(i)}{5(i)} \left(\frac{W_{\mathrm{CI}_i}}{\sum_{j=1}^{j=11} W_{\mathrm{CI}_j}} \right) \tag{1}$$

In this formulation, CI represents the community importance, C is the QOL parameter condition, and W_{CI} is the weight of community importance for the QOL parameter i. The individual weight is compared to the total weight placed on all 11 QOL parameters. The weighting parameter is expressed in Eq. (2)

$$W_{\mathrm{CI}} = f(Low, Medium, High) \tag{2}$$

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Energy dependence connects the social requirements to the technical requirements. Energy dependency can have direct and indirect impacts. For example, powering a fan may improve physical well-being directly and emotional state indirectly. Based on the introduction of an electrically powered device, the demand would also likely continue to increase. The relationship between the condition and applied energy dependence weight is represented in Eq. (3)

$$\mathrm{ED}(i) = \frac{5 - C(i)}{5(i)} \left(\frac{W_{\mathrm{ED}_i}}{\sum_{j=1}^{j=11} W_{\mathrm{ED}_j}} \right) \tag{3}$$

ED is the energy dependence, C is the condition, and W_{ED} is the weight of energy dependence for the QOL parameter, i. The weight, W_{ED}, would be based on information obtained from the community. The method for quantifying the weight variables is not part of the current study. Therefore, we assume values for the weight to demonstrate how it would be used in our framework. The weight used in our study will be one of three qualitative levels as represented in Eq. (4)

$$W_{\mathrm{ED}} = f(\mathit{Low}, \mathit{Medium}, \mathit{High}) \tag{4}$$

The conditions of the parameters range from 0 to 5, with 0 corresponding to low levels of satisfaction and 5 corresponding to high levels of satisfaction. In Eqs. (1) and (3), a condition level of 0 corresponds to a higher value for CI and ED, thus indicating a higher need for these conditions. Similarly, a high condition rating indicates the CI and ED variables are more likely to be satisfied for the particular QOL parameter.

Weights for the community importance and energy dependence are assumed for this study. In the implementation, the rating would be determined through survey data. Energy dependence would also be related to the quantity and energy consumption of electrical devices associated with the particular QOL parameter. In this work, we use a rudimentary low, medium, and high scale for both parameters to demonstrate the use of our framework. The corresponding numeric values are thirds of 1:0.33, 0.66, and 0.99, respectively. Equation (5) is the sum of the results of Eqs. (1) and (3)

$$\mathrm{CS} = \mathrm{CI} + \mathrm{ED} \tag{5}$$

where CS is the combined score of the community importance, CI, and energy dependence, ED. The sum of the community importance and energy dependence components allows for comparison between the parameters. However, it is also necessary to compare the community importance and energy dependence separately. Creating objectives with respect to the parameters through the design process can support advancements in QOL. For Eqs. (1), (3), and (5), a higher value would indicate a greater need for intervention. This concerns the priorities of the community and the ability for energy access to make an impact. Based on the calculated value, the parameters can be compared. The higher the value, the greater the importance to the community and the greater the energy dependence. This comparison elucidates the areas where energy-related solutions could provide the greatest impact. The outcomes of this model aim to support design and operating decisions with applications in power management.

The community importance is one driver of the anticipated change in condition. Improving the condition of a given QOL parameter can be set as an objective, based on community values. By determining what energy devices will be required to achieve that change, energy demand can be estimated. This model is envisioned to aid in the power management strategy. In the case of demand exceeding the capacity of the system, the allocation of available resources needs consideration. The intermittent nature of renewable resources and occasional maintenance issues present scenarios that can affect energy production. The variations in energy consumption can occur on a day-to-day basis, or through long-term events that accompany development. An example of the latter is the growing number of electrical devices acquired by those living in the community.

By understanding the areas where energy can effectively improve QOL, the system requirements are developed. After the energy system is implemented, the QOL assessment can be repeated. As the condition, community perspective, and energy dependence of the parameters evolve, the operational requirements can be modified. This process is updated to continue to improve the QOL by updating the parameters for the energy devices added over time. This proposed process allows the microgrid to maintain a reasonable level of operation as growth occurs. Moreover, it provides a useful understanding of the community dynamics and energy needs to support system upgrades in capacity.

2.2 Blocks D and E: cDSP for Power Management. Developing operational procedures that are aimed at uplifting QOL can be accomplished by prioritizing energy loads. Prioritization should be based on the 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 Fig. 3. It is assumed this system can also power loads using stored energy. A conceptual understanding of the system is needed in formulating the cDSP.

2.2.1 Overview of the Compromise Decision Support Problem. The cDSP is a hybrid of mathematical and goal programming. This tool is used to find *satisficing* solutions [21]. We develop a set of goals to be met for the system operation. These goals are based on system information and 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 problem is formulated by identifying system variables, constraints, and goals. The cDSP is organized into four categories; *given*, *find*, *satisfy*, and *minimize*. When goals conflict, a compromise is made, and the cDSP provides solutions representative of the possible outcomes. These solutions are not optimal but satisfactory. 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, deviations for the target values for each of the goals of the system are minimized. The specifics of this process are available in Ref. [21]. The cDSP is commonly used in design. However, the cDSP can be used for system operation. The solutions from the cDSP are energy allocations for each load. In this section, we demonstrate the framework that incorporates QOL in power management decision-making.

2.2.2 Application of the cDSP and Scenario Planning. The cDSP is applied to control 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 that 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 QOL with the cDSP mathematically incorporates these considerations. The solutions from the cDSP correspond to energy load

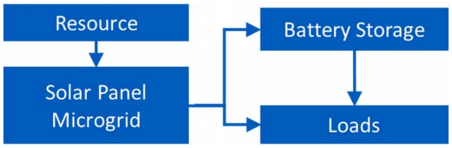

Fig. 3 General conceptual model of a microgrid

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allocations based on 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 objectives of this problem are to reach the target demand for each load. These requirements are formed to maximize the positive societal impact or minimize the practices impeded by limited access to electricity. The goals are derived from the QOL model, Block B. The end requirements are formatted as goals in Eq. (6)

$$\frac{P_i t_{it}}{PT_{it}} + d_i^- - d_i^+ = 1 \tag{6}$$

where P is the power, i is the number of loads, and t is the time period. In Eq. (6), 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 the target value of the variable. Equation (6) 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 shown in Eq. (7). Two deviation variables exist as follows: underachievement of the goal or overachievement of the goal [21]. 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
- S_{it}: energy storage

Deviation Variables

- d_i^-: underachievement
- d_i^+: overachievement

$$D = \sum_{i=1}^{n} W_i^*(d_i^- + d_i^+); \ \sum_{i=1}^{n} W_i = 1 \tag{7}$$

In Eq. (7), 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 production capacity. Energy dispatched for the loads cannot exceed the amount produced. The energy demand or anticipated demand is necessary for 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 demand, production, and storage are defined in constraint Eq. (8). The conflicts between the goals are also related using this equation. Power allocated to one load cannot be allocated to another

$$S_{t+1} = S_t + P_g t_{gt} - P_1 t_{1t} - P_2 t_{2t} - P_3 t_{3t} \ldots - P_n t_{nt} \tag{8}$$

In Eq. (8), S_t is the current energy in storage and $P_g t_{gt}$ is the energy generated. The remaining terms, $P_n t_{nT}$, 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. The boundaries of the system are determined through the supportive information provided by Block C. The list below describes the boundaries for each variable.

Boundaries

- $P_{ti} \geq 0$: Energy demand is assumed to be greater or equal to 0
- $S \geq 0$: System storage is assumed to be greater or equal to 0
- $S \leq S_{Batt}$: Storage cannot exceed the capacity of the battery
- $d_i \geq 0$: The deviation variables must be greater or equal to 0
- $d_i^- \cdot d_i^+ = 0$: One deviation must have a value of 0 so that the product is 0

The cDSP formulation for energy resource allocation is summarized in Table 3. In Table 4, the village characteristics are described for the example.

The resource allocation formulation using the cDSP is adaptable to varying requirements. This is especially critical as we develop components of a method that can be applied to diverse settings. Another important consideration in this formulation is the time component. Incorporating the time dependency is another feature that contributes to the adaptability of the formulation.

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. The weights are applied to each of the deviation variables in the minimization equation. 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 the formulation presented in this work is that only three variables can be used. When more than three variables exist, the problem is structured differently. The structure of the problem can be adjusted by modifying the formulation of the objectives and goals. A key feature of the formulation is the flexibility for adapting to different conditions. Adaptability is important for variations that occur from day to day as well as those that occur throughout the system life. We

Table 3 cDSP formulation

Given	Maximize the energy demand that is fulfilled
Find	*System variables* S_t $L_{1t} = P_{t1}$: Load 1 $L_{2t} = P_{t2}$: Load 2 $L_{3t} = P_{t3}$: Load 3 L_{it}: Load i
Satisfy	*Deviation variables* $d_i^-, d_i^+ = 1{:}3$ *System goals* $\frac{P_i t_{it}}{PT_{it}} + d_i^i - d_i^+ = 1$ *System constraints* $S_{t+1} = S_t + P_g t_{gt} - P_1 t_{1t} - P_2 t_{2t} - P_3 t_{3t} \ldots - P_n t_{nt}$ *System bounds* $P_{ti} \geq 0$ $S \geq 0$ $S \leq S_{Batt}, d_i \geq 0, d_i^{-*} d_i^+ = 0$
Minimize	*Deviation function* $D = \sum_{i=1}^{n} W_i^*(d_i^- + d_i^+); \ \sum_{i=1}^{n} W_i = 1$

Table 4 Example village characteristics

Parameter	Existing resources	Required resources
Water	Wells	Pump system
Safety	Streetlamps powered less than 1 h at night	Multiple lights per home, streetlamps powered longer
Education	Classroom	Multiple lights per classroom and home, projector, computer
Leisure/ Social	Common meeting place	Cooling fans

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can explore alternative solutions within the space, or update the requirements to generate a new solution space. For short-term changes in requirements, exploring alternative solutions within the space may be sufficient. However, if these solutions are not fitting, we can also compute a new set of solutions. Additionally, the formulation can be changed to include additional generation, demand, or storage components to appropriately represent the system. This is also crucial for the application of the method for different communities.

The cDSP allows us to develop a solution space for the allocation of available energy. It allows us to 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 variations in community needs. The requirements are developed using the QOL 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 within the solutions. As the community's needs change over time, suitable solutions can be selected. The inputs of the framework can also be updated to reflect new requirements. The framework is developed to integrate QOL and power management to support decision-making.

3 Results and Discussion

An example is presented to demonstrate how the framework can be implemented to allocate energy for microgrid power distribution. A problem is set up consisting of two scenarios that vary in the level of energy demand. The context for this example is based on what has occurred in rural villages, such as Kudagaon, India. SunMoksha has provided significant information to enable our analysis.

3.1 Quality of Life. In this paper, we examine four QOL parameters. These parameters are associated with power loads for water pumps, streetlamps, and households. Water pumps are indicative of the *water* parameter. Streetlamps represent the *safety* parameter. Household energy corresponds to the *education* and *leisure* parameters. The resources are related to the QOL parameter to identify possible impacts. Table 4 describes typical resources and electrical needs for a rural village that has recently been electrified. Using the characteristics of the community, the model inputs are developed. The model inputs for the condition, community importance, and energy dependence are in Table 5, and the outputs are represented in Fig. 4. The ratings are assigned to the parameters based on information provided by SunMoksha.

Table 5 Example village model input

Parameter	Condition	CI Rating	ED Rating
Water	1	0.99	0.99
Safety	2	0.99	0.99
Education	3	0.33	0.33
Leisure/Social	4	0.99	0.66

Examining the outputs of the model, water and safety have the highest scores. Therefore, these factors should be prioritized in the formation of design requirements. For energy dependence, water and safety have the highest scores. It is important to examine the community importance and energy dependence scores both combined and individually. The combined scores permit comparison across parameters. Analyzing the scores separately allows us to determine how the energy system can provide impact. Using this information, we develop requirements for the system. In this example, system requirements should support water and safety. The information from the QOL analysis is used as inputs for the cDSP.

3.2 Available Power and Demand Loads. From the QOL model, water and safety are high priorities. The priority 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 QOL model results. When power production exceeds demand, the batteries are charged. The stored energy is used later when the demand is greater than production.

For the study, we assume 80 households use two lightbulbs, one television, one fan, and one mobile charger for 6 h per day in the evening. For the entire community during daylight, three water pumps would be used for 6 h per day, and in the evening, street lamps would be powered for 12 h per day. Demand changes from day to day and seasonally, as well as increases over time. For example, a fan may need to be used on a warm day but not on a cold day. We can modify the requirements defined in the cDSP to incorporate these time-dependent considerations. The baseline demand will be 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 h. 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 called, "Daytime", corresponds to the hours between 6 a.m. and 6 p.m. The second time period called, "Nighttime," corresponds to the hours between 6 p.m. and 6 a.m. In the *Daytime* period, there is

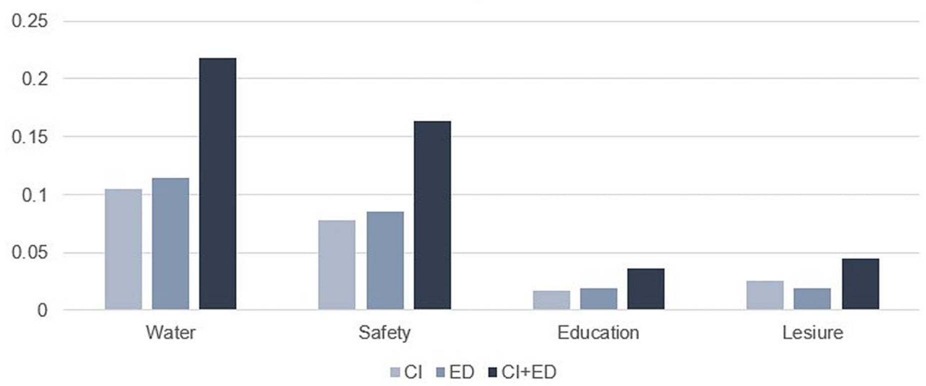

Fig. 4 QOL parameter conditions for CI, ED, and CS(=CI + ED)

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Table 6 cDSP problem formulation

Given	Maximize the energy demand met
Find	*System variables* S_t $L_{1t} = P_{t1}$: Load 2 (water) $L_{2t} = P_{t2}$: Load 2 (safety) $L_{3t} = P_{t3}$: Load 3 (household) *Deviation variables* $d_i^-, d_i^+ = 1{:}3$
Satisfy	*System goals* $\frac{P_1 t_{1t}}{PT_{1t}} + d_1^- - d_1^+ = 1$ (6.1) $\frac{P_2 t_{2t}}{PT_{2t}} + d_2^- - d_2^+ = 1$ (6.2) $\frac{P_3 t_{3t}}{PT_{3t}} + d_3^- - d_3^+ = 1$ (6.3) *System constraints* $S_{t+1} = S_t + P_g t_{gt} - P_1 t_{1t} - P_2 t_{2t} - P_3 t_{3t}$ (8.1) *System bounds* $P_{ti} \geq 0$ $S \geq 0$ $S \leq S_{Batt}$ $d_i \geq 0,\ d_i^{-*} d_i^+ = 0$
Minimize	*Deviation function* $D = \sum_{i=1}^{n} W_i^* (d_i^- + d_i^+);\ \sum_{i=1}^{n} W_i = 1$ (7.1)

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. Using two time periods, we illustrate the functionality of the framework for time-dependent problems. The application of the cDSP and the flexibility of the formulation are demonstrated through two problems. The cDSP formulation for these problems is summarized in Table 6. Equations (6.1)–(6.3), (7.1) and (8.1) correspond to Eqs. (6)–(8), but are specific to the problem.

The energy demand for each load is the target value for the respective goal. The loads are determined through the QOL analysis. The variables and boundary conditions are determined by the system specifications. The constraints for the cDSP relate the energy production and consumption and the stored energy. 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 QOL model.

3.3 Problem Formulation.

The cDSP is exercised for two problem scenarios to validate the proposed technique. The problem demonstrates how the cDSP is used for resource allocation. 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 6 h, 12 streetlamps for 12 h, and 70 households 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 adaptability of the model is illustrated using Scenario 2. This is achieved by examining how changes to the solution space impact power management. The combination of these cases allows us to understand what is needed to sufficiently meet the needs of a community and how these requirements change over time. The results of the problem support the validity of the method. The target values for Scenario 1 are summarized in Table 7.

Table 7 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

We present the results from the cDSP using ternary plots. Ternary plots are used to visualize feasible solution regions among three variables. The sum of the three weight variables is unity at every point in this plot. The weight given to each respective variable is plotted using the grid method. <> With this method, each edge of the triangle represents a variable weight that ranges from 0 at the origin to 1 at the opposing end. Thus, the grid lines for that variable will be parallel to the edge that is connected at the origin. More information about ternary plots can be found in Ref. [1]. The feasible region is found by applying different weights to each of the variables.

The water demand load is shown in Fig. 5(*a*). The line depicted on the plot and the key provides a boundary where the desired solutions lie. The arrows emanating from the line point toward the possible solutions. In the case of water needs, the target value for energy demand exceeds supply. Since the target cannot be achieved, the goal is to meet as much of the demand as possible. The ternary plot for the streetlamp load is shown in Fig. 5(*b*). This load is indicative of the safety parameter in the QOL framework. 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(*c*) is the ternary plot for the household energy. This corresponds to the education and leisure parameters in the QOL. The feasible region among the three variables is shown in Fig. 5(*d*). This space is found by superimposing the three aforementioned plots. Points inside the superimposed feasible space represent feasible operating solutions that are satisfactory for all three variables.

The combined region, shown in Fig. 5(*d*), is the part of the solution space that would balance the three variables. In the system operation, energy could be allocated to each of the loads. These solutions correspond to how the variables are weighted. A solution can be selected based on the QOL needs at a given time. 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 of each target value 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 QOL.

Based on what the community needs, the selected solutions can be changed. All of the loads may be needed but have different priorities. 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 would be non-zero and within the combined region. Depending on the community requirements and the availability of energy, there may be situations in which the goals change. For instance, solar energy may be more plentiful at certain times of the year. During these times, more household energy may be desired. Accordingly, the solution selected could correspond with a higher weight applied to the household variable. Depending on the situation, the demand for other loads could also decrease. This could occur when appliances or devices are not required during a given time period. Thus, the corresponding weights of the other loads are reduced. Within and beyond the combined space, multiple solutions exist.

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

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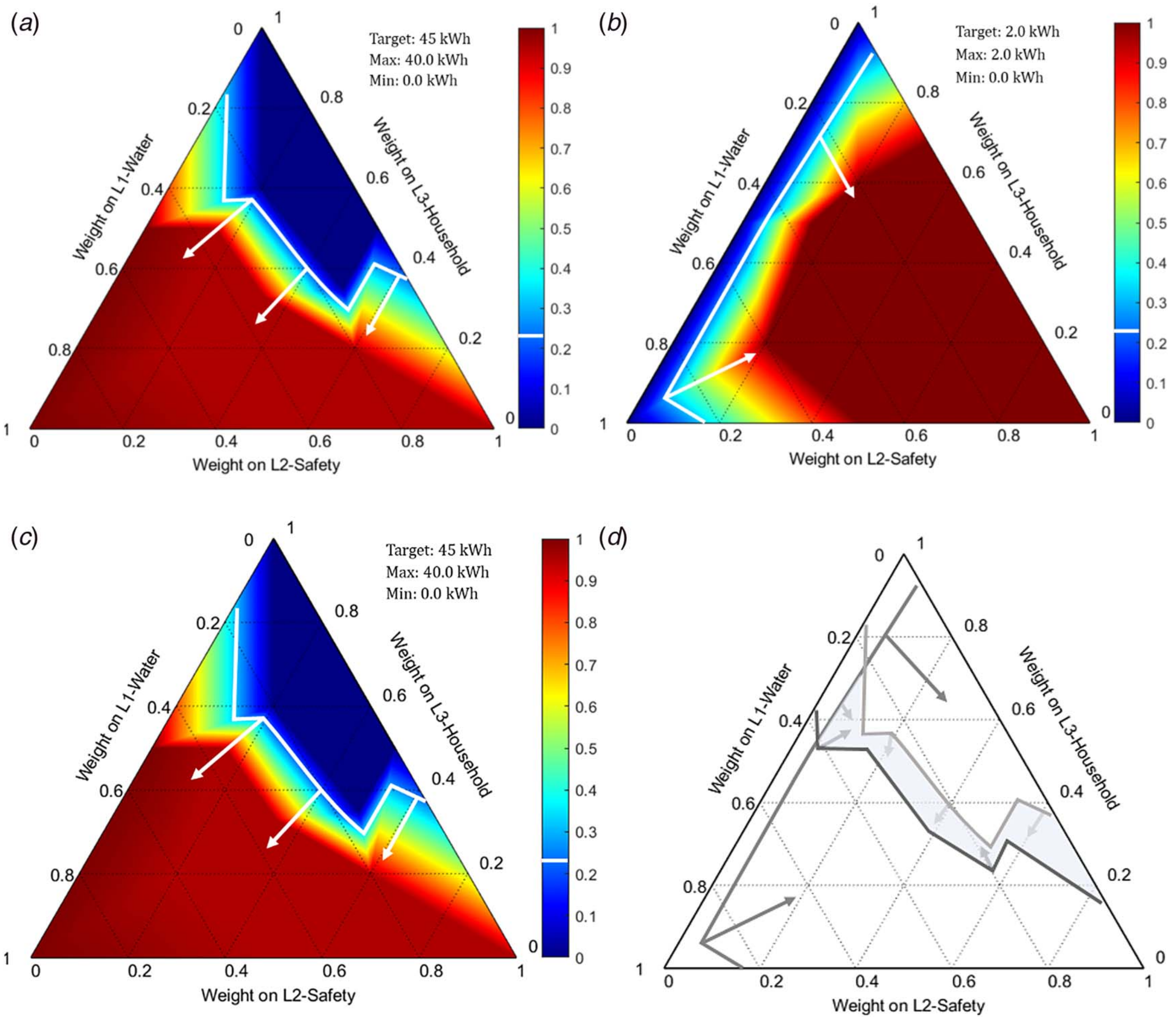

Fig. 5 Ternary plots representing feasible operating space for the (*a*) water, (*b*) safety (*c*) household loads, and (*d*) collective the operating solutions

scenario analysis provides insight as to what solutions should be chosen given the community's status. These needs will change, and the framework allows for this essential adaptability of the microgrid. If the solution space is too restricted, or not appropriate for the community, the social entrepreneur can redefine the requirements. Scenario 2 is similar to Scenario 1, although the target goal values have been cut in half and rounded to the nearest integer. The target values for Scenario 2 are outlined in Table 8.

Reducing the goals for each of the variables is expected to increase the solution space given the same available energy resource. In Scenario 1, the target water load exceeds the produced energy. In Scenario 2, this value is less than that of 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 many of the target values as possible. Proportionally, the safety load is much smaller than that of the water and household loads. For QOL, 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 and would warrant upgrades to the microgrid.

Table 8 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

Modifying the requirements within the cDSP changes the solution space and the energy allocation. The combined ternary plot for Scenario 2 is shown in Fig. 6. With the assumption that the demand exceeds the supply, decisions are required in allocating the available energy. Within the combined region, each of the QOL parameters is 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

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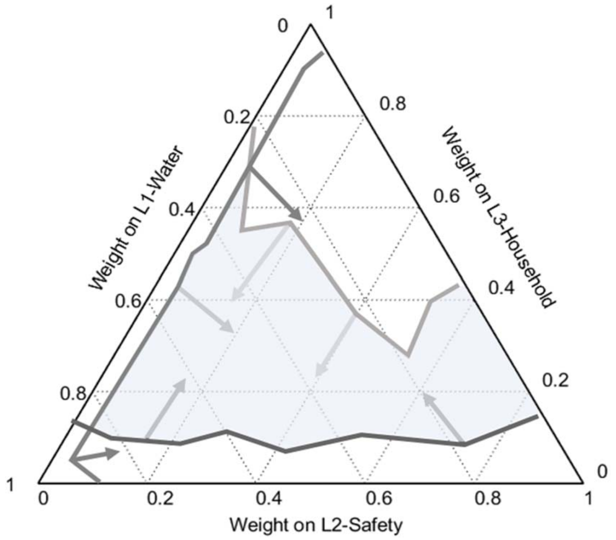

Fig. 6 Combined ternary plot Scenario 2

Table 9 Problem output comparison

Scenario	Available energy	Water (kWh)	Safety (kWh)	Household (kWh)
1	40	38	2	0
2	40	39	1	0
1	40	38	2	0
2	40	23	1	16

have now been reduced. The analysis of the problem provides insight into power management by changing the solution space. This 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 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. The results from the cDSP for which water and safety are prioritized in Table 9. The water and safety loads are prioritized per the QOL model.

Of the four entries in Table 10, the first two correspond to when the household demand has no priority, and the last two correspond to when the household demand has some priority. The solutions that do not prioritize the household demand lie outside of the combined region of the ternary plot. The results that have some priority are within the combined space. These solutions were selected as water and safety loads have high priority. 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. Not only can we prioritize the water and safety energy loads, but we can also determine the impact of applying different priorities to the household demand. The connection to QOL is represented by examining possible scenarios and the expected outcomes of the power allocations. Scenario planning is used to anticipate possible events that may arise and match those to solutions from the cDSP.

The results of the cDSP seem reasonable for the physical interpretation of the energy allocations. The load allocations do not exceed the amount produced and are bounded by the system constraints. If available energy is allocated to one of the variable loads, the amount remaining is allocated to the other load(s). This is one indication that the power management model is providing verifiable results. Different starting points are used to examine the consistency of the results and the convergence of the solutions. Additionally, applying different weighting combinations to the deviation variables resulted in the expected outcomes for each of the load variables. For example, if the variable associated with the water-energy demand was weighted higher than that of the safety or household demand, more energy would be allocated to that variable. The results of the different weighting schemes support the verification and validation of this framework. The deviation variables remain bounded between 0 and 1 for each computation of the cDSP, supporting the validity of this formulation. This indicates the cDSP is working as expected. With the assumptions defined in the problem formulation, the cDSP appears to present verifiable and valid results.

In the example 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 QOL 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 QOL model, power 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 10. The scenarios selected correspond to the prioritization of the three loads. The scenario where water and safety are prioritized was selected based on the QOL model. The remaining scenarios are chosen to demonstrate the change in energy allocation based on load prioritization. While other scenarios exist, this set is compiled to illustrate how the results of the cDSP will change according to the needed load(s).

The solutions from the cDSP are mapped to possible situations in Table 10. 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

Table 10 Power management scenarios

Load priority	W1	Water load (kWh)	W2	Safety load (kWh)	W3	Household load (kWh)	Storage (kWh)
Water and safety priority	0.5	38.0	0.5	2.0	0.0	0.0	2.0
Household priority	0.0	0.0	0.0	0.0	1.0	40.0	40.0
Household and safety priority	0.0	0.0	0.5	2.0	0.5	38.0	40.0
All priority	0.33	23.0	0.34	1.0	0.33	16.0	17.0

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to minimize the difference between the targeted demands and variable values. This power management strategy allows for the flexibility to accommodate different types of events and provide possible solutions. Alternate solutions can be selected for time-dependent changes in requirements. In Table 10, the emphasis is on the prioritized loads. However, as presented in Table 9, many solutions may exist for a given scenario or prioritization of the loads. 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 QOL 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 10, the scenario solutions are related to the expected impact on the QOL parameter(s).

Having data and the associated knowledge about the Kudagaon village is crucial to understanding QOL and defining the microgrid requirements. When the generation cannot meet the demand, preventing hindrances to the QOL is important. Access to electricity is expected to improve QOL. Therefore, continuing that improvement is needed especially when there is insufficient available power. And in some cases, although improvement is not feasible, mitigating the lack of available power is the only option. Naturally, there is a prioritization required. Energy needs to be allocated to the most necessary loads. Identifying which loads are most necessary should be connected to the defined QOL for each community.

For example, in Kudagaon, the use of streetlamps allows for safer commutes, socialization, and protection from animals. The streetlamps provide safer walking conditions as snakes can be seen more easily. Lighting in houses has allowed more time for chores and school work. And by powering fans, some people can sleep better. Not only does this information help establish operational requirements, but it also provides insight into how lifestyle will change what is needed of the technical system. Allocating energy to safety, water, or household demand is more than just powering lights, fans, and pumps. Ensuring these devices 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 QOL and microgrid operation allows us to provide solutions that are sustainable and resilient. The impact of technical intervention can be substantial, but only if that system continues to uplift and empower the community. Therefore, we must continue to work toward solving problems that inhibit progress and empowerment.

4 Closing Remarks

A framework is proposed for decision-based power management of microgrids in rural communities. A key feature of this framework is a socio-technical model that is used to explore the relationship between energy use and social well-being. The components of the framework are intended to be adaptable to different community needs and to changes that occur in those communities over time. A model for representing the QOL is also presented. The model includes a set of QOL parameters, each of which is evaluated through the community importance, and energy dependence components. We use the parameters and three components to assess the non-technical factors in system operation. The water, safety, education, and leisure/social activity, and QOL parameters are connected to powering water pumps, streetlamps, and household devices. In the example presented, the water and safety parameters need prioritization. Power management solutions are achieved by balancing the energy supply and demand through the cDSP. The cDSP formulation and solutions are derived from the QOL of the community. We join the non-technical and technical domains through the components of the framework. A test problem is examined to demonstrate the function and flexibility for time-dependent changes of the framework. This is achieved by considering possible scenarios and modifying the requirements to expand the solution set. As needs change, human decision-makers can select appropriate solutions or update the cDSP. In accordance with the QOL analysis, the test problem solutions selected correspond to prioritizing water and safety loads. Additionally, other solutions that prioritize different loads exist. As needs change, these options are available. The framework is iteratively updated such that the solutions continue to fit the community's needs with time-dependent changes. As renewable energy systems become more prevalent globally, the concepts developed in this paper can be applied in a variety of settings.

This study demonstrates the ability of this framework to make decisions on load management. Examples demonstrate how the load priorities can be mapped to community needs using QOL as the basis. We recognize the challenges and uncertainties in relating the QOL to energy use at this point in the process. The proposed framework provides a means by which we can *begin* to explore this relationship. The QOL parameters may be modified as guided by additional work. Still, these parameters provide useful inference to reason-based load management. The collaboration with SunMoksha provides a field application in which the socio-technical model may be validated and refined. This will be part of the ongoing work and future reporting. The ability to iteratively update the framework allows for solutions to reflect the community's progression. Representing different communities requires simple adjustments to the formulation. The framework presented could be applied to different communities and other types of resource allocation problems with modifications to the inputs or structure of the formulation. For example, the cDSP can easily be altered if multiple generation sources or a greater number of loads need to be included. In the QOL model, if the problem is not an energy resource but rather something else, the dependence factor could be changed to represent the resource needed. The framework is developed to be flexible and conceptually applicable for other systems. The approach offers a perspective for systems operation based on QOL. Introducing systems that are supportive of promoting and maintaining QOL is crucial for sustainable development.

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Nomenclature

d = deviation variable
t = time (h)
C = condition
L = energy load (kWh)
P = power (kW)
S = energy storage (kWh)
W = weight
CI = community importance
ED = energy dependence

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