The Need for Teaching Place-Based Contextualization for Sustainable Power System Infrastructure Design

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Abstract—In this paper, we make the case for an increased focus on teaching an understanding of societal context and the integral role it plays in energy infrastructure design. Power system design education is inadequate in terms of holistic understanding of the non-technical aspects of a client-society in the development of energy infrastructure solutions. These are reflected in many failed designs, primarily designed by student engineers as part of capstone projects, senior design projects, or extra-curricular work through humanitarian-oriented programs administered by NGOs. We are developing coursework that introduces students to the complexities involved in the practice of engineering in rural communities at the international level.

Index Terms—Contextual engineering, energy infrastructure, non-technical design factors, power system education, societal context.

I. INTRODUCTION

In the field of power engineering, achieving maximal electrification for all aspects of human infrastructure has been a goal for some time now. This goal has only become more acute due to the imminent climate change crisis looming upon us. The push today is to attempt to achieve this electrification through renewable energy sources to the maximum extent possible [1]. A significant number of published research articles in the power engineering field are devoted to the development of novel methods of generating, transmitting, distributing, utilizing, converting, or controlling renewable energy resources. These articles often preface their research objectives by alluding to the need to improve energy efficiency, reduce the impact of climate change, and make universal access to energy economically feasible.

For nearly 1 billion people on Earth, reliable access to energy (or complete lack thereof) remains a chronic problem, often referred to as energy poverty [2]. Reducing this energy poverty by improving access to reliable and cost-effective energy through electrification has benefits, including increased economic opportunity and productivity through the utility value of electricity [3], increased literacy rates [4], increased educational opportunity through improved internet access [5], improved health service delivery [6], to name just a few.

In recognition of this need for electrification and the associated benefits that may be realized, many non-profit organizations are focused on humanitarian applications of electrical engineering, and many encourage—indeed, are specifically geared towards—participation of engineering students [7]. Several humanitarian engineering (HE) non-profit organizations have student chapters on university campuses where students engage in HE projects as extra-curricular activities. Examples of such organizations include Engineers Without Borders (EWB), Engineers in Action, and Engineers for a Sustainable World (ESW). The IEEE itself has started major HE initiatives towards improving electrification, and encourages students and young professionals to get involved. Examples include IEEE Smart Village [8], IEEE Humanitarian Activities Committee (HAC) [9] and IEEE Special Interest Group on Humanitarian Technology (SIGHT) [10]. In several instances, universities themselves provide students with hands-on project-based learning (PBL) courses or senior design capstone projects in the curriculum to advance issues towards—participation of engineering students [7]. The opportunity to participate in such projects allows engineering students (the “soon-to-be” professional engineers) to appreciate their technical training, and realize their ability to make meaningful impacts. These curricular and extra-curricular activities train engineering students with the ultimate aspiration that they will join the workforce as socially responsible and competent technical professionals, who use their specialist knowledge for the humanitarian application of science and technology to better the human condition.

The outcome of many of these activities are the design, construction, and installation of remote energy systems to facilitate reliable energy access in rural communities that have conventionally been out of the purview of the bulk power grid due to various reasons. Several follow-up studies done on these rural energy systems across the world however, find that the success of these systems is far from assured [11] [12]. Sociological investigations into the failed outcomes of the rural energy systems find that the designers often fail to account for the more subtle non-technical aspects of a client-society for

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whom the infrastructure is designed and how those can possibly influence the technical aspects of energy infrastructure [13][14]. This seems to indicate that despite the best of intentions, and despite all the resources that have been spent in creating socially responsible engineers, we somehow missed teaching some crucial aspects of the design process in engineering education. As pointed out in [15], designing for industry is not the same as designing for community.

The objective of this paper is to demonstrate the need for student engineers to realize and recognize that engineering design and the consequent success of engineered infrastructure is dependent as much on the non-technical influences of a client-society’s socio-cultural identity as it is on the student engineers’ technical expertise and prior experience. A need for understanding societal context in engineering design is crucial, as is the need to recognize subconscious biases in the practitioner’s approach to design. We refer to this whole paradigm succinctly as contextual engineering [16].

The rest of the paper is organized into three sections. In Section II, we describe the crux of the formulation of design frameworks, and the need to understand and appreciate the social context in the design of engineered systems, particularly in societies that have developed on a very different trajectory. We explain why we believe this appreciation should be taught to student engineers and how this understanding can help us develop more holistic design frameworks. In Section III, we describe coursework that we have developed (and are further refining) to present contextual engineering in a structured format. The various aspects of the coursework are described. We also present an observational tool developed to help attune student engineers when working with client-societies in the field. In Section IV, we present some results of our use of the observational tool during fieldwork visits and discussions and insights based on them. In Section V, we provide some closing remarks, as well as our vision for the future work that we plan to do.

II. THE NEED TO APPRECIATE AND TEACH SOCIETAL CONTEXT

The technical aspects of microgrid design have been heavily focused on in the literature [17] [18], and several design frameworks have been proposed. A popular framework is the objective optimization-based design framework. The crux of this design framework may be stated in the form of an optimization problem as

$$\begin{align*}
\max \quad & J(x) \\
\text{s.t.} \quad & \mathbf{g}(x, p) = 0 \\
\quad & \mathbf{h}(x, p) \leq 0. \\
\quad & x \in X.
\end{align*}$$

(1)

In this framework, the decision variable \( x \) represents the collection of design variable values which can be optimized over, belonging to the set of all possible design variables values \( X \). The set \( P \) represents the collection of system or site parameters, and \( p \in P \) is a specific element which represents the system or site parameters specific to a particular site. The function \( J : X \rightarrow \mathbb{R} \) is some objective that represents the quantity to be maximized. It may be the generated energy, system efficiency, or utility value of the generated energy, among several other possibilities, including a weighted combination thereof. The functions \( g : X \times P \rightarrow \mathbb{R}^m \) and \( h : X \times P \rightarrow \mathbb{R}^n \) represent \( m \) equality and \( n \) inequality constraints, respectively, that are reflective of physical limitations. The nature and form of the constraints depend on the nature of the problem and the modeling approach adopted. A solution of the above problem, denoted by \( x^* \), thus represents a set of optimal values of the design variables that achieves the maximization of the stated objective under the specified constraints and parameters. Variations in this optimization-based design framework have been proposed, and the variations relate to how the system is modeled, the solution method(s) being utilized [19] [20], and specific aspects of the problem that are addressed [21].

In practice, microgrid system design (similar to system design in any engineering discipline) tends to be somewhat more complicated. As engineering design is the discipline of negotiation, and negotiation requires reconciliation of conflicting objectives, these negotiations often necessitate analyzing trade-offs. To that end, frameworks that are better able to capture the trade-offs inherent to the design process may be utilized [22]. These trade-off-based design frameworks rely on multi-criteria analysis (MCA) for decision making. The MCA problem may be stated as

$$\max \ \{ f_1(x, p), f_2(x, p), \ldots, f_r(x, p) \}$$

$$x \in X.$$

(2)

Each function \( f_i : X \rightarrow \mathbb{R}, i = 1, 2, \ldots, r \) represents some objective that is being evaluated, for a total of \( r \) objectives. The objectives may involve system efficiency, utilization, or system reliability, among other options. These are often also referred to as criteria. The maximization in (2) is a somewhat loose term, as no single \( x^* \in X \) can simultaneously maximize every \( f_i \) for \( i = 1, \ldots, r \). Methods to solve these multi-criteria problems may break down the problem into a hierarchy of subproblems [23], or try to rank the criteria by some measure of preference [24] [25]. Design frameworks have also been proposed that combine both of the above frameworks to develop multi-stage design frameworks [21] [26] [27]. It is vital to recognize that these frameworks are prescriptive, in that they merely provide guidelines on how the design process should be approached [28]. The onus of determining exactly what constitutes the constraints in (1) or criteria in (2) to be included is left to the designer.

The factors which ultimately determine the constraints or criteria involve the technical as well as the non-technical aspects of the design problem. The precepts that govern the complex interactions of place, culture and identity of client-societies (which collectively comprise the non-technical aspects) most often manifest themselves in terms of implicit behavioral practices, shared outlook towards technology, and collective predisposition to interacting with designer practitioners external
to the community. Being attuned to these factors is crucial for student engineers and design practitioners if they are to design infrastructure that will serve the communities sustainably and enduringly. The uncertainty in dealing with these multi-factored--and often unspoken--ground rules of interaction is admittedly daunting. As such, the difficulties in quantification of the non-technical aspects lead to them being put aside in the design process, to the detriment of design process and the suitability of the ultimate outcome.

Recognizing, internalizing and working harmoniously with the uncertainty associated with qualitative information requires conscious effort developed through practical human interaction and application, aspects that purely technical coursework alone cannot possibly prepare students for. As [29] points out, student engineers tend to be heavily techno-centric. To overcome this, more innovative and holistic approaches to teaching engineering design have been developed. These recognize the need for the “human-technology interface” element in design, and indeed encourage the need for interactions between the technical and non-technical aspects of the design process. Some examples of these holistic approaches include co-designing with client-society [30], human-centered design [31], and project-based learning (PBL) [32][33]. These holistic approaches are designed to help students recognize and become more comfortable with the process of understanding the connections between engineering design and the people who will interact with the designed system.

The one major issue that these approaches do not address, however, is the fact that they remain centered around the students engineers’ educational outcome. PBL and other international service engineering approaches such as project-based service learning (PBSL) [32][33]. These holistic approaches are designed to help students recognize and become more comfortable with the process of understanding the connections between engineering design and the people who will interact with the designed system.

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The approach, then, should be to develop student engineers’ cognitive abilities to perceive the unique context that defines every client-society, and to develop a more community-centric technical design framework. We envision that a contextually-developed design framework can be derived from (1) as

\[
\begin{align*}
\max \quad \tilde{J}(x) \\
\text{s.t.} \quad \tilde{g}(x, p, q) &= 0 \\
\tilde{h}(x, p, q) &\leq 0, \\
x &\in X.
\end{align*}
\]

Here, we envision \(q\) to be a set of some additional parameters of the design problem that represents some measure of the unique contextual aspects of the client-society under consideration. The notational change \(\tilde{J}, \tilde{g}\), and \(\tilde{h}\) from (1) may be necessary. Similarly, a contextual version of (2) can be developed as

\[
\begin{align*}
\max \quad \{f_1(x, p, q), f_2(x, p, q), \ldots, f_r(x, p, q), \\
f_{r+1}(x, p, q), \ldots, f_{r+k}(x, p, q)\} \\
x &\in X,
\end{align*}
\]

where the societal contextualization of the standard MCA design framework is reflected by the addition of \(k\) additional criteria \(f_{r+1}, \ldots, f_{r+k}\), as well as the modification of \(f_i\)’s in (2) to some appropriate \(f_i\) for \(i = 1, 2, \ldots, r\).

III. APPROACH

Through extensive prior work done in directing student-led international engineering projects in developing countries, the second author has developed frameworks of contextual engineering. It is a means to an end, and seeks to attune designers to recognize their unconscious biases as they approach the design process, and how they perceive their role in their interactions with the client society.

A. The Foundations of Contextual Engineering

Contextual Engineering draws upon the social sciences to evaluate place- and people-based conditions to determine appropriateness of a technical infrastructure for a given set of people. Contextual methodology follows a series of processes, beginning with evaluator calibration of understanding through self-reflection, then examining global conditions that contribute to a place’s identity and values, and assessing stakeholder motives for project participation. Armed with this knowledge, the evaluator visits and closely interacts with the client society to identify and quantify the five key socio-economic influences that together create a unique fingerprint of technical capability using a predictive tool developed and tested for this purpose. We refer to these as the contextual influences, and label them as: Economic, Political, Cultural, Educational, and Mechanical [16]. The terms do not correlate directly with their dictionary definition, and we describe them briefly below:

1) Economic influence: Economic influence does not refer to the presence or absence of money, but instead indicates how difficult it is for a client-society’s inhabitants to meet what they consider as their basic needs. In that sense, it is a
reflection of their resource-constrained condition. A high economic influence is an indication that a client-society will have difficulty in maintaining infrastructure that requires a lot of resources for its upkeep.

2) **Political influence**: Political influence indicates the presence of political dynamics and class divide in a client-society. High political influence suggests that power is a significant driver for that society, and the failure to identify power dynamics in infrastructure design can create conflict and rejection by sectors of the population.

3) **Cultural influence**: Cultural influence is an indication of how prominently a client-society’s cultural identity colors their worldview and defines the scope within which they interact with technology. A high cultural influence is an indication of a very strong adherence to a value of identity belief, which must be recognized and respected in engineering design. Infrastructure and technology that is disruptive to their identity as a people is likely to see poor uptake.

4) **Educational influence**: Educational influence describes a client-society’s interaction with knowledge. It is a measure of their propensity to acquire and disperse new information and understanding. A high educational influence is an indication that a client-society is generally receptive to more technologically advanced solutions and has the intellectual inclination to maintain and operate them.

5) **Mechanical influence**: Mechanical influence describes the “handiness” of a client-society. It demonstrates the resourcefulness that their members exhibit when working with their available pool of resources. A high mechanical influence is an indication that complex technical aspects of a system or infrastructure can be serviced using local labor.

We would like to emphasize that our classification of the nebulous concept of societal identity into these five influences is not an exclusive means of contextual analysis. Other classifications are theoretically possible, and indeed, have been proposed in various forms [13]. The categories we use have been based on our personal experience from empirical observations of nearly five dozen rural communities across the globe, and we have found that the results of the predictive tool are able to distill the qualitative observations of what makes each of these communities unique in a succinctly understandable and quantifiable way. Furthermore, these categories are also useful in advising the design practitioner in how the pertinent design variables of an off-grid energy system are likely to be influenced by the community during a co-design phase. In light of this, we have worked on developing coursework for teaching context in international interventions.

**B. Coursework: ABE 498 - Context in International Interventions**

We have developed coursework that seeks to bring the nuance of context into the educational process by exposing engineering students to the social sciences and practical case studies of western interactions with non-industrialized client societies. It is offered under the title *Context in International Interventions* to all engineering majors as an elective, listed under the department of Agricultural and Biological Engineering and is co-listed for non-engineering students under the Center for African Studies. Typically, enrollment consists of half engineering students and half non-engineering students at study levels from freshman to PhD graduate levels. The course recently was approved for fulfillment of non-western cultural and social science general education requirements. The syllabus and teaching materials for the course have been developed based on the second author’s extensive experience working on student group-led humanitarian projects in North, Central, and South America, Western Africa, and Southeast Asia. The salient features of the coursework focus on the factors first presented in [36].

The course discusses aspects of the design process and the intricacies of applying them to other societies.

1) **Engineering and Development**: International service engineering usually has a global development undercurrent, and seeks to further integrate client-societies into the global economic structure. The connotation of globalization and its perception by isolated client-societies is focused upon. Depending on the client-society in question, they may perceive globalization as the unleashing of new opportunities or an external intrusion on their way of life. The implicit objective of addressing infrastructure needs to achieve global developmental goals is discussed, as is the need to separate the two.

2) **Standards**: The prescriptive or excessive use of global engineering design standards and how it can affect system design in a way that alienates client-society members is discussed. How, why, and whether globalized standards should be used when designing remote systems for rural communities are considered. Discussions also focus on the development of place-based design standards and their comparative merits and drawbacks over global design and test standards.

3) **Motives and Objectives**: The potential for conflicting objectives among project participants is examined. A failure on the part of the designers to recognize that their own reasons for participating in the project may differ from the explicit and implicit motives of funding source, regulatory agency, local facilitator, and community itself, can lead to disputes over performance or cost, for example.

4) **Appropriate Technology**: The development and applicability of appropriate technology [37] is discussed. Case studies of appropriate-technology informed modifications to standardized technology deployments are presented to help students understand the innovative mindset often displayed by client-societies with out-of-the-box thinking.

5) **Economic Engagement**: The approaches to pricing models of utilities are discussed, and what kinds may be considered appropriate for which communities depending on the contextual influences they display.

Research articles relevant to the above topics are assigned as weekly readings which provide background, context, and illustrative case studies. Reflection-type questions are assigned based on reading materials. Throughout the duration of the course, a specific case study of a failed water distribution infrastructure in Western Africa is used to illustrate the concepts taught in
It helps the practitioner to better associate nuances of behavior, identity, and place-based practices into some classifiable categories which make intuitive sense.

The second author has developed an influence identification tool [38], available publicly at [39], to provide some measure of quantification to the socio-cultural aspects of a client society. The tool is an observational data-gathering assessment developed using ethnographic observations and is geared towards technical practitioners who travel for project-related work to communities whose identities are distinct from their own. The tool is a questionnaire of 41 questions, with each question scored on a 1-5 Likert-type scale. The completed questionnaire can be returned to obtain a report of client-society scores. Fig. 1 shows an example of how the results are typically returned in the generated report. These scores are a relative measure of each of the five contextual influences as they pertain to the client-society, with the measures themselves being presented as a percentage. An ideal community is one in which each influence holds equal emphasis (20%), and no single influence is considered more or less important than any other. Deviations from the ideal value for the influences are indicative that certain influences define the client-society more than others. The tool serves two main purposes:

- It helps to direct the practitioner’s thought process into that frame of mind where they become more attuned to make societal observations and recognize their subconscious biases.

We would like to emphasize that the numerical results of the predictive tool are less important than the recognition given to the contextual factors by the practitioner when interacting with the client-society. The present version of the influence identification tool has been extensively tested for use in rural communities in an international setting. A domestic version of the tool has also been developed and is currently undergoing testing within the United States.

IV. CASE STUDIES AND RESULTS

A. Student Development

The students who have participated in the current coursework, as well as the predecessor course on which ABE 498 is based, have been extensively interviewed to gauge the development of their skills concerning contextual listening and empathy building as it relates to international engineering development projects. Content analysis of transcribed interviews revealed that the students had developed empathy, as well as an understanding of the complex interactions between the technical and nontechnical aspects of engineering design.

We have found that the formal teaching of the technical and nontechnical aspects of project work should be emphasized so that students may experience them both simultaneously. Students complete the course with a dawning sense of understanding of, and appreciation for, client-society context in terms of the five contextual influences. By and large, the student groups are able to agree that international service learning projects can be approached so as to adequately address client-society needs, and that their efforts are less likely to result in non-sustainable outcomes. They are also able to recognize the realization that they are not the stakeholders to define objectives, but should provide their informed opinions to allow for decision-making to occur collaboratively. Project designs and outcomes become more nuanced when the dominant contextual factors become the primary drivers in decision making. Self reflection is a powerful tool that the students gain through the course. Formal and continual reflection, as stimulated through the reflection questions administered in the course, helps student practitioners learn about their own personal motivations and objectives, and also understand how these may influence their approach to the project. Student recognize the relevance of their technical training and are able to understand the societal context in which it is applied. Their informed opinion of the technical aspects, when in conflict with the client-society’s desires, set the stage for the management of expectations.

The results presented in this subsection can be found in more detail in [41].

B. Use Cases of the Predictive Tool

While developing a course on the intersection of art and technology, the second author made a trip to the rural community of Tikonko in Sierra Leone, West Africa, accompanied with
two teaching assistants (TAs). Once there, they interacted with members of the community, exchanged ideas, and made general notes about their observations in the community. Based on their field notes and observations, all three participants filled out the predictive tool and submitted them for analysis. The results of the predictive tool outcome are shown in Fig. 2.

By the analysis of these observations, it was found that all the participants’ observations were able to agree that the community shows a pronounced educational influence, thus indicating the underpinning that the community displays an inclination towards—and places an emphasis on—knowledge acquisition. Additionally, all three participants’ observations were in agreement of relatively low mechanical influence, an indication that the community does not show a particular adeptness at hands-on creative problem solving. For the other three influences, there was no unanimous agreement on the trends. This was a starting point of the conversations to recognize context, where the participants began to discuss their understanding of the society based on their observations, and how it may be used for the design of methods for information exchange. Subsequent research and evaluation of tool use explored the benefit of obtaining multiple perspectives individually and later averaging them together, as opposed to having individuals conduct observations then collectively complete the tool through negotiation [42].

To highlight how contextual engineering, along with the predictive tool, may help to highlight the unspoken and non-obvious (to an external practitioner) rules of social interaction in a client community, we present another result obtained by the use of the predictive tool by a group of student engineers, shown in Fig. 3. The community in question is the rural Andean village of Calcha, located in the Department of Potosí, within the Bolivian Andes. The community is comprised primarily of indigenous people of Quechua heritage who maintain strong ties to their traditional way of life. Somewhat unsurprisingly, the results of the predictive tool show that the community displays a higher than average relevance on cultural identity, indicated by the positive deviation of the cultural influence. What is perhaps more surprising is that they do possess a greater predisposition to acquiring knowledge as well as greater mechanical aptitude. In addition, the student engineers observed that interactions among community members involved a type of symmetric reciprocity. These interactions were characterized not so much by monetary exchanges, as much as a sense of obligation owed to the one another in the community. This also can be demonstrated through the very low political influence, which suggests there is not really a power dynamic that governs relationships in the community (in other words, they exhibit a pronounced sense of communalism). Unbeknownst to them, the student engineers were observing a social rule of engagement—called ayni—in action. Ayni is a basis of cultural interaction that anthropologists and ethnographers who have studied traditional Andean communities have long recognized as a uniquely Andean phenomenon. It refers to a social construct of mutualism or reciprocity, characterized by the understanding that when one member of a community receives from another, it creates a social obligation for them to give something in return [43]. The concept of ayni is often invoked to mobilize shared labor during construction or harvest periods, as well as the exchange of draft animals for tilling or field fertilization.

Knowledge of this cultural phenomenon, as well as the understanding that the community displays a high mechanical and educational influence, can help the attuned practitioner to design engineering systems with certain salient characteristics:

- The high mechanical and educational influence allows a more sophisticated system to be designed, with the confidence that the community has the inherent drive to acquire the knowledge necessary to maintain it.
- They possess mechanical competence to initiate quick repairs to the system, if needed.
- The concept of shared labor can be utilized to create a maintenance protocol using the social contract for the labor required for system maintenance.
A design consensus can be achieved by working with the governing board of the community to respect everyone’s needs because there is not much likelihood of dispossessed residents with such a low political influence.

The discussion above went into quite a bit of the non-technical aspects that characterize a client-community’s identity, but we wish to emphasize that these are the types of unknowns of a community that form a quintessential part of the trade-offs that must be accounted for in the design process. The contextual influences help define constraints or criteria such as design complexity, need for specialized labor, ongoing maintenance costs, etc., into design frameworks defined by (3) or (4).

V. CONCLUSIONS AND FUTURE WORK

We have presented our thoughts on the need for incorporating a shift in the teaching of power system engineering education (in particular)—and engineering design education in general—that attempts to encourage student engineers to realize that the engineering design relies as much on the contextual aspects of societal identity as the technical aspects of site. The issue of no-consequence design has been discussed. We have presented some of the steps we are taking at the University of Illinois to address these issues through coursework we have developed to teach contextual engineering. Various aspects of the coursework are described. An influence identification tool that helps student engineers to better appreciate the distinctness of every client-society is presented. Results of the use of the influence identification tool, what they reveal, and how they spur contextual discussions are presented. The results also form the basis to developing more holistic design frameworks. As we previously mentioned at the end of Section III.C, we have developed a domestic version of the influence identification tool and are currently evaluating and testing its use within the U.S., based on ongoing research conducted in underserved or disadvantaged communities within the United States. Case studies of such communities located within the U.S. include some rural farming communities in the state of Illinois as well as communities within Native American reservations in the American Southwest.

Future work in this area for us entails the development of tools similar to the influence identification tool to substantially incorporate contextual factors into the conceptual holistic design frameworks as outlined by the optimization framework in (3) and the MCA framework in (4). We envision our future work to also focus on the development of a comprehensive bi-level iterative design framework that brings together the MCA and optimization frameworks. The results from the influence identification tool will be incorporated into this robust hybrid mathematical framework. This comprehensive framework will use the contextual analysis and identification tools to determine the criteria that the client-society considers most relevant for their needs. Once a general feasible design space is identified based on these criteria, the optimization framework will be used to determine the optimal design variables. We are working on developing descriptive mixed methods approaches incorporating ethnographic survey methods to provide a systematic way to identify and quantify societal context so that they may be incorporated into the contextually-conscious frameworks presented in (3) and (4). Iterations between the two frameworks are envisioned as necessary as they reflect the real-life interactions where design practitioners and client-society members negotiate needs and manage expectations, thus necessitating modifications to the criteria or design variables throughout the design process.

The outputs of the investigations for the development of these tools as well as the comprehensive design framework will be used to create power engineering-specific courses on the design of sustainable remote energy systems.

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