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Adaptive capability and socioecological traps: a bioenergy case in communities of Irapuato, Guanajuato, Mexico

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Abstract

Background Energy poverty, which is the deprivation of a series of energy services that satisfy human needs, affects over 2 billion individuals who rely on the combustion of biomass and other solid fuels to fulfill their energy needs. While certain communities address their energy shortfall by harnessing local natural resources, these alternatives fail to provide access to more advantageous and sustainable conditions, thus leading to what are commonly referred to as socioecological traps.

Results This research studies the relationships between the energy alternatives that two communities have developed, the bioenergy capability that would allow the system to access more desirable and sustainable states, and the costs and benefits that are perceived from this new use of their residues and resources. A quantitative methodology was employed by designing and applying a structured questionnaire applied to 207 households in two energy-poor communities in the municipality of Irapuato, Guanajuato, Mexico: San Agustín de los Tordos and El Comedero Grande. We have inferred that the alternatives generated by the communities function as socioecological traps. On the one hand, these options generate adverse effects on the health of people and the environment, while discouraging the construction of bioenergy capabilities; on the other hand, they allow them to cover some training costs, at least in the short term. These discoveries suggest that the system is currently in an advantageous phase of the cultivation of new capabilities.

Conclusions The outcomes of this study contribute significantly to enhancing our comprehension of socioecological traps and capabilities within the realm of energy, thereby offering valuable insights for the effective management of successful bioenergy implementation initiatives. Moreover, these findings enable the development of frameworks for theoretical interpretation and methodological application within specific contexts, exemplified in our case by rural communities in Irapuato, Guanajuato Mexico. The holistic approach reveals that while individuals may have alternatives to fulfill their energy requirements, many of these alternatives can inadvertently become socioecological traps. For instance, the use of firewood as a short-term solution for household energy needs can generate adverse health and environmental consequences in the long run. In the light of these considerations, a study of their nature becomes imperative and relevant as it delves deeply into the intricate relationship between compensatory alternatives and capacities. Simultaneously, it scrutinizes the community's perception of bioenergy in terms of costs and benefits, with the overarching goal of transitioning toward a sustainable energy system.

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Keywords Energy transition, Renewable energy, Community-based research, Ecological sustainability, Biodiversity conservation

Background

Human development has been inextricably linked to energy, whose consumption is carried out in increasingly more intensive ways and larger quantities. Consequently, the availability of energy for citizens and households, especially in the rural context, is a great concern at a global level [1–3].

In [4], the authors point out that about 2.4 billion people depend on the combustion of biomass and other solid fuels to meet their energy needs. Some communities alleviate the energy deficit with the use of natural resources in their environment; however, these alternatives do not allow them to access more favorable and sustainable states, therefore becoming what are considered as socioecological traps [5, 6]. It is crucial to emphasize the existence of numerous communities in the world lacking access to any energy alternatives. Similarly, some communities possess the means to access various forms of energy generation, but these options remain financially out of reach for their economies. This situation presents a significant challenge in establishing sustainable energy systems. The focus of this study is primarily on rural communities, where social, environmental, economic, and cultural factors intricately influence energy usage. Throughout this research, we delve into these characteristics to understand the complexities surrounding the implementation of energy solutions in such areas.

The most common alternative is the combustion of firewood. Firewood is the most economical fuel available to people in rural communities, and its use has cultural components [7]. However, the combustion generates respiratory diseases in people who are in direct contact, such as women and children, and reduces the tree coverage of the communities, and firewood collection occupies a large part of people's available time, time that they could dedicate to income-generating activities, education, or free time [8].

The adverse effects of the generation of alternatives in a situation of energy poverty are contradictory in the rural context where there is an abundance of agricultural and livestock waste that can be used in the generation of bioenergy.

Energy poverty is the deprivation of a series of energy services that satisfy human needs [9]. Regarding a measurement threshold to consider a population in energy poverty, a household is there when it cannot have adequate energy services with 10% of its income [10]. This indicator can be complemented with elements that account for how energy scarcity prevents the satisfaction of basic human needs [9].

It should be noted that clean energy is conducive to alleviating energy poverty, contributes to the promotion of employment and the growth of household income, improves the health of residents, and reduces their medical expenses [3, 8].

In Mexico, the potential for solid biofuels is estimated at around 2500 petajoules (PJ) per year, which would satisfy approximately 28% of the primary energy demand [11]. Even when bioenergy production in Mexico is not profitable for private initiatives [12], bioenergy production can be a very favorable choice for rural communities [13].

Moreover, substituting fossil fuels for renewable energy is an effective way to reduce carbon emissions and achieve sustainable development. For this reason, community-led bioenergy projects hold great promise for addressing a variety of issues faced by remote and indigenous communities [13, 14]. However, there is little research dedicated to better understanding what makes projects successful and to reducing uncertainty among agricultural producers about the costs and benefits of their implementation [13, 14].

This article presents a case study in the global south, in communities of Guanajuato, Mexico. These populations are in a situation of energy poverty, both because of the expense generated by the purchase of energy and the adverse effects of satisfying their basic needs.

The case study is developed in two communities: San Agustín de los Tordos (20.78382548670681, − 101.42760326665535) and El Comedero Grande (20.81542, − 101.23657), both in the municipality of Irapuato, Guanajuato, México. These communities are in a situation of energy poverty.

Led by the Center for Research and Advanced Studies of the National Polytechnic Institute (CINVESTAV-IPN), these communities will begin to use bioenergy as part of the project "Production of biofuels for rural use from agricultural waste through the optimization of microbial consortia using metagenomics," sponsored by the National Strategic Programs (PRONACES) from the National Council of Science and Technology (CONACYT). In this project, a consortium of researchers, including local community investigators, has developed an innovative strategy for utilizing agricultural and livestock residues sourced from both communities to fuel bioreactors. Furthermore, they will employ cutting-edge genomics methodologies for the optimization of biogas production, with the primary objective of mitigating the reliance on firewood. This initiative has far-reaching implications for the preservation of endemic trees within the region, as well as for the overall well-being and time availability of the local population.

In this context, the communities have undertaken a diagnostic process to gather essential information crucial for the successful implementation of this bioenergy initiative. This proactive approach reflects their commitment to ensuring the project's effectiveness and sustainability. Through such efforts, these communities are not only harnessing bioenergy but also fostering a brighter, more sustainable future for themselves, guided by the invaluable insights gained from the initial diagnostic process. The research aims to show the relationship between compensatory alternatives in the face of energy scarcity, the bioenergy capacities that the community has already developed, the costs that bioenergy produces, and the benefits that the community perceives from implementing the project. The relationships between these variables allow us to know each community's situation and the opportunities and challenges to be faced.

Therefore, knowledge of these relationships is essential to understand the challenges and opportunities of implementing a new form of energy in the community system and to have a successful implementation of the bioenergy initiative. In this context, it is possible to affirm that "there is a good relationship between bioenergy and rural development" [3], p. 311].

The following sections expand on the theoretical elements, the research context, the methodology used, the results and discussion, and the conclusions.

Research model and hypothetical approach

The socioecological systems approach is an alternative to overcome the separation between human beings and the environment. From this approach, it is understood that human activity takes place amid a complex interaction and as part of a system conformed by social and natural components [15].

The community can be identified as a socioecological system characterized by a particular way of inhabiting the environment. This understanding of reality is based on an ancestral tradition that is expressed in current elements such as social relationships and practices, the sense of territory, management criteria, and the struggle to defend community resources [16].

Furthermore, it is recognized that production, distribution, and consumption within energy systems have links to multiple social and ecological processes. In this context, research that contemplates the socioecological dynamics of the system and its resilience processes is necessary [17].

It is the community that adopts a position in the face of a problem according to how disasters or threats affect them and the access they must have to resources to generate and activate strategies to face them [18] so that the understanding of the problem and the formulation of alternative solutions are socially constructed elements.

It is necessary to point out that traditional knowledge is not static but is recreated daily in the acts, facts, and circumstances of the human being toward the divine, nature, family, community, and society in general. In this way, the development of new capabilities around energy can be explained, because it includes actors and technology from outside the community that, if favorably incorporated, can provide the system with greater resilience through better use of its resources [18].

As the community is an open system, it can be assumed that expectations, experiences, and prior knowledge have already been generated in the use of biomass, even if it has not been done intentionally and at an exceptionally low intensity. This is because the development of capabilities cannot be separated from history, the concrete circumstances, and the purposes of the community and, especially, the material and symbolic reproduction of life.

Therefore, the hypothetical approach is based on five hypotheses described as follows:

H1: Compensatory alternatives have a negative influence on bioenergy capability.

Faced with energy poverty, communities develop compensatory alternatives through forms of energy savings, the use of devices for greater efficiency, and the use of natural resources in their environment, such as light and natural heat or firewood, e.g., [19]. Although these options initially offer an energy solution, they also have negative social and environmental effects, which worsen over time, so they could be considered socioecological traps. When considering the potential development of a new capability, the system must conduct an evaluation that compares the alternatives it has previously employed with the new capability [20]. It is important to note, as highlighted by [21], that the primary obstacle to adopting renewable energies lies not only in their economic cost but also in technological and social aspects. Furthermore, understanding the benefits that the new option can bring to the system is essential.

H2: Compensatory alternatives have a negative influence on the willingness to bear the costs for the use of bioenergy.

The alternatives allow the community to alleviate its energy deficit, a state of conformity is created, in which the community must feel comfortable and achieve resistance to change, specifically for the construction of new capabilities.

The economic cost is the main obstacle to the adoption of renewable energy, since a lot of capital is needed for its implementation [22, 23]. Several studies show that there is a negative link between cost and consumers' willingness to accept renewable energy [24–26].

H3: Compensatory alternatives have a positive influence on the perceived benefits of bioenergy.

Regarding the benefits of bioenergy, there are those related to a positive environmental impact, social benefits, and new work options for the community. However, the feeling of the cost–benefit of bioenergy varies depending on the experiences of each case [27].

Due to the negative effects of the alternatives on the well-being of people and the natural environment, it can be thought that people are increasingly aware of these negative effects and aspire to a better relationship with their environment, to greater well-being. That is, there is a desire to access a more sustainable state due to the discomfort that compensatory alternatives generate.

H4: Costs have a negative influence on bioenergy capabilities.

Compensatory alternatives, at least in the short term, are generating a small surplus of time and money that can be used for training in the use of bioenergy, which can reduce costs. This means that they act against the costs of training. The costs for the development of new capabilities, in this case, bioenergy, discourage their implementation.

H5: Capabilities have a positive influence on the benefits of bioenergy.

In contrast, a positive influence of bioenergy capability on bioenergy benefits can be assumed due to the real possibilities that bioenergy has on the achievement of social benefits. Figure 1 shows the relationships between variables proposed in previous hypotheses.

Study context

The project is performed in the State of Guanajuato, Mexico. Guanajuato is one of the 32 federal entities of Mexico.

The State of Guanajuato is made up of 46 municipalities; the communities included here are part of the municipality of Irapuato, Guanajuato. Figure 2 shows their location in this municipality.

Both San Agustín de los Tordos and El Comedero Grande are rural communities in Irapuato. In the state territory, Irapuato is distinguished by being part of the so-called region III, the center, which concentrates most of the population of the entity, although it represents a quarter of the territory; 67% of the inhabitants of the entire state are in this region, and Irapuato is the second most populous municipality in Guanajuato (see Fig. 2).

San Agustín de los Tordos has a population of 1427 inhabitants, who constitute 331 households. El Comedero Grande has a population of 389 people, congregated in 105 households [28]. The families of these communities are mainly dedicated to agriculture; although, there is also some mobility to work in the surrounding industrial or service areas.

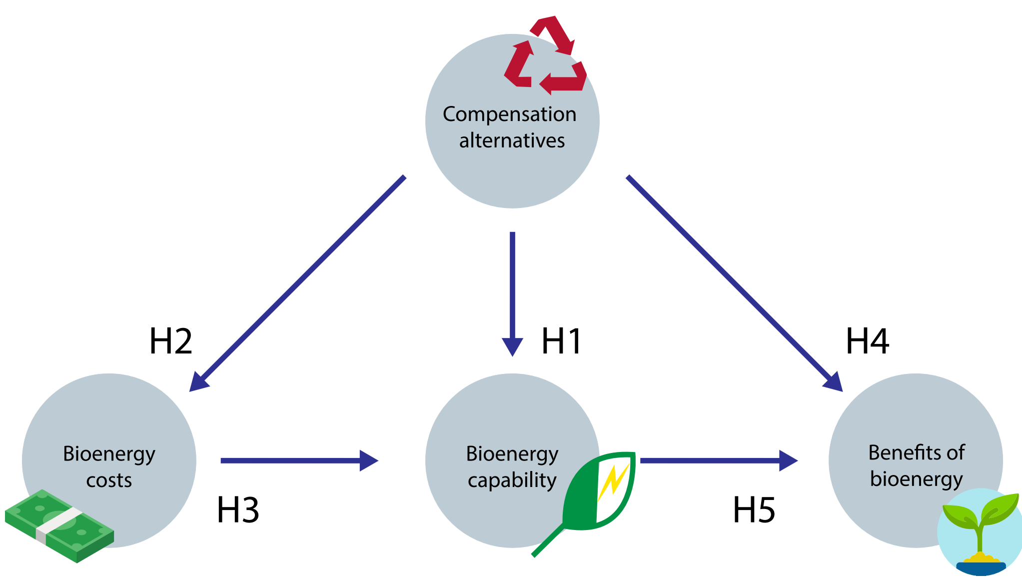

Fig. 1 Relationships between variables proposed in previous hypotheses

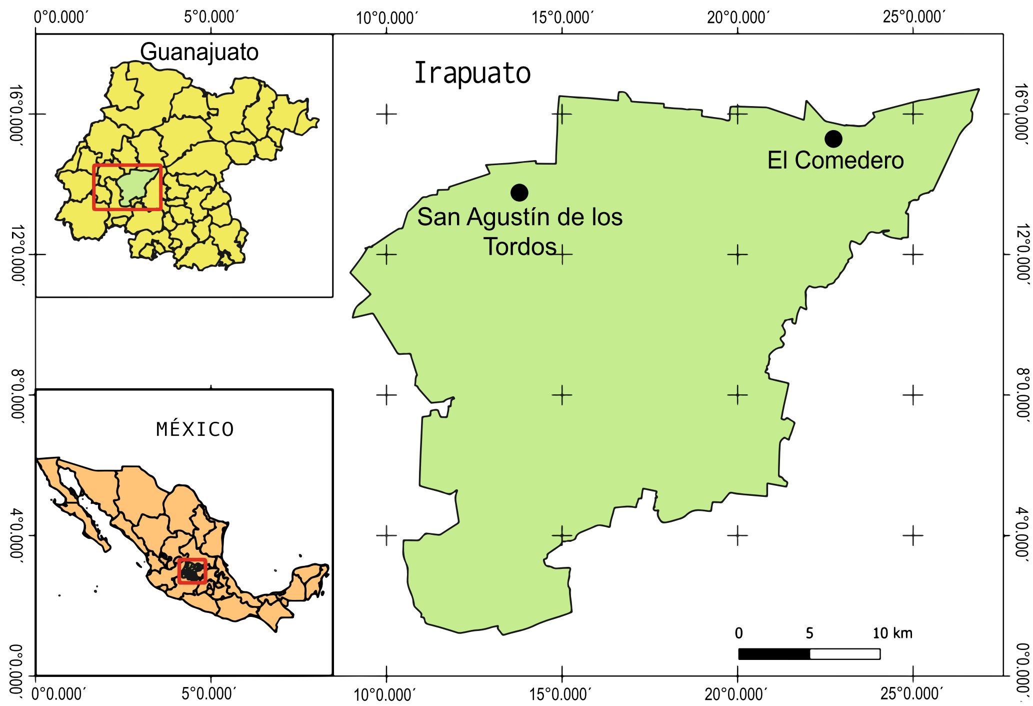

Fig. 2 Location of the communities San Agustín de los Tordos and El Comedero Grande in the municipality of Irapuato, Guanajuato, Mexico

Methods

A cross-sectional and explanatory study was carried out to prove the proposed hypotheses. To compile the data, a structured questionnaire was developed and given to heads of families of San Agustín de los Tordos and El Comedero, Irapuato, Guanajuato, Mexico.

The variables were integrated starting with a reduction of factors through principal component analysis with Varimax rotation and Kaiser normalization. With the data obtained, a partial least squares structural equation modeling (PLS-SEM) analysis was performed using Statistical Package of the Social Science (SPSS) version 21.

Questionnaire

A structured questionnaire was designed on the basis of the literature review on the topic [20, 21, 24–27] to analyze the composition and relationships of the following variables: energy alternatives, bioenergy capability, bioenergy costs, and bioenergy benefits.

The questionnaire was composed of 24 valid questions (see Appendix 1, questionnaire in Spanish), and they were answered based on a five-point Likert scale ranging from 1 (completely disagree) to 5 (completely agree). The data collection method was the survey, and the information collection techniques were face-to-face interviews.

Variable operationalization and measurements

Compensation is the way communities deal with scarcity problems. For example, in the face of the water crisis and the impossibility of growing food, they choose compensatory alternatives such as purchasing food from external resources, e.g., [29, 30]. In the energy field, it is observed that in the face of energy scarcity, alternatives are used to compensate for the deficit, such as firewood and animal manure [31]. In the case of this research, it is noted that, on the one hand, people try to reduce the consumption of liquefied petroleum (LP) gas, and on the other hand, they resort to using firewood and natural heat that is collected, which has lower costs.

Moreover, capabilities enable the integration and configuration of skills, resources, and competencies to effectively respond to the evolving demands of the environment [32]. Within the energy sector and across European nations, valuable technological and innovation capacities have been recognized in the context of energy technological advancement, e.g., [33]. This study unveils foundational capacities that individuals have acquired, either tacitly or explicitly [34], specifically concerning their knowledge on the use of biomass, as well as their willingness to utilize waste for bioenergy generation.

Bioenergy capacity encompasses understanding and experiences around biomass, and the degree to which the community perceives the use of bioenergy as beneficial. Bioenergy costs refers to the barriers, difficulties, costs, time, effort, money, and other aspects, for the implementation of bioenergy. The benefits of bioenergy are the results that the new form of use can generate.

The items used to measure the variables of the study are presented in Appendix 1.

Sample

In terms of energy usage within these communities, the primary priorities for households revolve around food preparation and electricity consumption. Concerning food preparation, there is a significant divergence in energy sources. While the use of LP gas is common, the prevalence of firewood usage is no less preponderant. Particularly, when cooking demands more extended periods, firewood becomes the preferred option to conserve LP gas due to its excessive cost.

Regarding the specific communities we collaborate with in this research, it has been established that their energy expenses exceed 10% of their earnings. This constitutes the initial indicator of energy poverty within these communities. Based on data gathered through our questionnaire, households report an average monthly income of $4,833 Mexican pesos, with more than 10% of this income allocated to energy expenses.

Households have an average of four members, 65% are headed by men and 35% are headed by women. Regarding the education of the head of the household, 85% report a middle school level, and 15% refer to taking a grade higher than middle level.

A total of 207 questionnaires were applied to households: 130 questionnaires were applied in the community of San Agustín de los Tordos, and 77 questionnaires were applied in El Comedero Grande. The snowball sampling technique facilitated the expansion of our network of informants, as they connected us with additional individuals who shared the requested information. While our approach proved fruitful, several constraints limited the extent of data collection. The prevailing risk of pandemic outbreaks made it imprudent to gather more questionnaires, and some informants expressed reluctance to participate. Additionally, the stringent time constraints imposed by the field trip's deadlines further restricted our data collection efforts. Despite these challenges, the sample we managed to collect is deemed adequate and suitable for the intended statistical analysis.

The sample includes 65% of households in both communities. With a medium effect size, statistical power of 0.8, a significance level of 0.01, and two predictors, the smallest required sample size is 82 units [35]. Thus, the sample size achieved ($N=207$) for this study is larger than needed.

Evaluation of models

The evaluation of the measurement model, the structural model, and the global model are presented below.

1. Evaluation of the measurement model.

To assess the measurement model, it is necessary to evaluate two other models: the reflective measurement model and the formative measurement model.

A) Evaluation of the reflective measurement model.

For the assessment of the reflective measurement model, construct reliability, convergent validity, and discriminant validity were considered.

For this measurement model, SmartPLS software provides the composite reliability index, Cronbach's alpha (A), and Dijkstra–Henseler's value (ρA). Values around 0.7 to 0.8 are adequate for strict reliability [36].

Convergent validity is considered as the degree to which a measure correlates positively with other measures from the same construct. It implies that a set of indicators stands for a single construct [37, 38]. This aspect is confirmed by verifying that the factorial loads of the indicators are higher than the minimum threshold of 0.7 [39]. An average variance extracted (AVE) value greater than 0.5 indicates convergent validity (Table 1).

Discriminant validity is assessed using cross-loading analysis, the Fornell–Larcker criterion, and the heterotrait–monotrait ratio (HTMT). The external loading of an indicator associated with a variable must be greater than its other cross loadings (its correlations) on the other variables in the model. In this way, it can be verified that no item is loaded with greater intensity on any construct other than the one it measures. The evaluation and report of the cross loadings are done using a table with rows for the indicators and columns for the variables.

The Fornell–Larcker criterion compares the square root of the variance values extracted from the AVE with the correlations of the latent variables. It verifies that the square root of the variance extracted from the mean of a variable is greater than the correlation of this variable with another variable [40, 41]. The final evaluation criterion of the reflective model is the calculation of HTMT. In a well-fitted model, the HTMT ratio should be significantly less than 1.

B) Evaluation of the formative measurement model.

In the formative model, each indicator is a dimension of the meaning of the latent variable. Dropping an indicator means that the variable loses part of its meaning, hence the importance of the indicators causing the construct. For the evaluation of the training model, three elements were used: weights, loads, and collinearity of the indicators [39, 42].

The evaluation of the formative measurement model includes assessing loads, weights, and multicollinearity [43].

Table 1 Reflective measurement model

Indicator	Loading	*A*	*ρA*	CR	AVE	Fornell–Lacker criterion					Cross-loadings				
Compensatory alternatives (COMP)						COMPF1	COMPF2	EDBIO	EOBIO	RBIO	COMPF1	COMPF2	EDBIO	EOBIO	RBIO
COMP3.Reduction of electricity consumption	0.916***	0.790	0.793	0.905	0.827	0.909					0.916	0.404	−0.282	−0.186	0.313
COMP4. Reduction of gas consumption	0.902***										0.902	0.345	−0.271	−0.161	0.284
COMP7. Firewood collection	0.816***	0.820	0.825	0.893	0.735	0.413	0.858				0.273	0.816	−0.268	−0.412	0.406
COMP8. Take advantage of natural light	0.884***										0.366	0.884	−0.302	−0.372	0.348
COMP9. Take advantage of natural heat	0.870***										0.414	0.870	−0.446	−0.373	0.478
Bioenergy costs (EDBIO)															
EDBIO1. Economic cost	0.792***	0.740	0.777	0.825	0.543	−0.304	−0.399	0.737			−0.140	−0.116	0.592	0.297	−0.197
EDBIO2. Difficulty getting new knowledge	0.787***										−0.201	−0.211	0.787	0.388	−0.242
EDBIO3.Lack of time	0.760***										−0.250	−0.311	0.760	0.163	−0.288
EDBIO4. Shortage of trainers	0.792***										−0.262	−0.411	0.792	0.466	−0.375
Bioenergy capability (EOBIO)															
EOBIO3. Earlier knowledge of biomass use	0.816**	0.793	0.799	0.879	0.709	−0.191	−0.448	0.448	0.842		−0.100	−0.408	0.446	0.816	− 0.242
EOBIO4. Earlier experiences with biomass use	0.903***										−0.203	−0.388	0.462	0.903	−0.360
EOBIO5. Acceptance of the new form of use	0.803***										−0.176	−0.334	0.213	0.803	−0.267
Benefits of bioenergy (RBIO)															
RBIO3. Improving the relationship with nature, especially the local flora	0.937***	0.878	0.888	0.942	0.891	0.329	0.479	−0.394	−0.347	0.944	0.260	0.442	−0.334	−0.292	0.937
RBIO6. Improved relationship with nature, wildlife conservation	0.951***										0.356	0.461	−0.406	−0.359	0.951

***$p \leq 0.001$

In this research, the variable compensatory alternatives (COMP) are considered formative variables because the items that make them up are causes or antecedents of the construct [44, 45]. These variables are each integrated from two factors: Comp1 and Comp2. In this way, the formative model of the investigation is integrated for two factors of compensation alternatives (Table 3).

2. Evaluation of the structural model.

The predictive relevance of the model was also calculated using Q^2 statistics, which measure the predictability of the data observed through the routing model. Values below 0.25 indicate small predictive accuracy, values between 0.25 and 0.5 indicate medium accuracy, and values greater than 0.5 indicate large accuracy [35, 38].

The adjusted value for the coefficient of determination (R^2) was calculated. The interpretation of this indicator is analogous to a regression: it stands for the joint effects of the exogenous latent variables on the endogenous latent variable. Values between 0.1 and 0.25 indicate a weak explanatory power, values under 0.5 are considered moderate, and values between 0.5 and 0.75 are strong [46].

f^2 indicates the degree to which an exogenous construct explains an endogenous construct in terms of R^2: $0.02 < f^2 < 0.15$ for a small effect, $0.15 < f^2 < 0.35$ for a moderate effect, and $f^2 > 0.35$ for a large effect [47]. According to Table 5, the effects are moderate.

3. Evaluation of global model

Finally, to evaluate the global model, the standardized root mean square (SRMR) value could be used. The model had a good fit for values under 0.08 SRMR [46].

Results

Evaluation of the measurement, structural, and global models

We assessed the validity and reliability of the dataset that conforms to the models used in this study: measurement, structural, and global. For the measurement model, we present the results of both the reflective and formative models. The last one shows that the selected indicators are reliable, showing significant Cronbach's alpha (A), and Dijkstra–Henseler's (ρA) values (Table 1).

Table 2 HTMT ratio

	Bioenergy costs (EDBIO)	Bioenergy capability (EOBIO)	Benefits of bioenergy (RBIO)
Bioenergy costs (EDBIO)			
Bioenergy capability (EOBIO)	0.578		
Benefits of bioenergy (RBIO)	0.452	0.411	

Table 3 Assessment of the formative measurement model

Compensatory alternatives (COMP)	Loadings	Weight	VIF
COMPF1	0.809***	0.550**	1.205
COMPF2	0.974***	0.871***	1.205

VIF Variance Inflation Factor

** $p \leq 0.05$; *** $p \leq 0.001$

The reflective model shows convergent validity, that is, the set of selected items represent a unique underlying construct, and it is observed in the acceptable values of AVE (Table 1).

Regarding discriminant validity, the Fornell–Larcker criterion (Table 1), cross loads (Table 1), and HTMT ratio (Table 2) are verified.

The formative measurement model shows acceptable values in terms of weights, loads, and collinearity of the indicators (Table 3).

The structural model was valued in terms of R^2, Q^2, and f^2. R^2 indicates the amount of variance of a construct that is explained by the predictor variables of the endogenous construct, whose values range from zero to one, and Q^2 indicates a measure of predictive relevance that allows evaluating how an exogenous construct contributes to an endogenous latent construct.

As can be seen in Table 4, the explanatory power for bioenergy costs (EDBIO, $R^2 = 0$ 0.175) is low, while the explanatory power for bioenergy capability (EOBIO, $R^2 = 0.264$) and benefits of bioenergy (RBIO, $R^2 = 0.263$) are moderate. Values for Q^2 correspond to small predictive accuracy for bioenergy costs (EDBIO) and bioenergy capability (EOBIO). Finally, Q^2 for benefits of bioenergy (RBIO) indicates medium predictive accuracy, while f^2 shows moderate effects (Table 5).

Finally, the global model had a good fit for values under 0.08 SRMR, and the fit index was 0.024.

Hypothesis testing

As for the hypothesis confirmation or refusal, we present in Table 5 a summary of such results.

H1 is accepted. First, the compensatory alternatives developed by the communities inhibit the development of bioenergy capabilities ($\beta = -0.305$, $p = 0.000$), since

Table 4 R^2 and Q^2 of the structural model

	R^2	Q^2
Bioenergy costs (EDBIO)	0.175	0.187
Bioenergy capability (EOBIO)	0.264	0.149
Benefits of bioenergy (RBIO)	0.263	0.273

Table 5 Path coefficients

	Path coefficient	Standard deviation	*T* statistics	*p* Values	f^2
Compensatory alternatives (COMP)- > bioenergy capability (EOBIO)	−0.305	0.068	4.512	0.000	0.218
Compensatory alternatives (COMP)— > bioenergy costs (EDBIO)	−0.423	0.061	6.991	0.000	0.105
Compensatory alternatives (COMP)—> Benefits of bioenergy (RBIO)	0.430	0.066	6.468	0.000	0.205
Bioenergy costs (RBIO)—> bioenergy capability (EOBIO)	0.313	0.066	4.718	0.000	0.110
Bioenergy capability (EOBIO)— > benefits of bioenergy (RBIO)	−0.159	0.069	2.296	0.022	0.028

they do not allow the problem of energy poverty to be viewed broadly. In the first place, they make it possible to deal with energy shortages by making use of elements from the environment such as firewood, which they can access and use relatively easily. Second, although the negative effects on health and the environment are known, especially from the use of firewood, cooking with this element has already been normalized, since ancient times and the opportunity cost involved has not been studied for women, especially, those who could take advantage of the extra time and effort in educational, health, and leisure activities.

H2 is accepted. The compensatory alternatives have a negative influence on the cost ($\beta = -0.423$; $p \leq 0.001$). The savings and the use of firewood to compensate for the energy deficit hurt the costs for the implementation of bioenergy, which means that the more compensatory alternatives are used, the more the costs for training will decrease.

It should be remembered that the compensatory alternatives act as socioecological traps, so it is necessary to take advantage of the window of opportunity that they are still generating since such beneficial conditions will disappear in the future.

H3 is accepted. The compensatory alternatives have a positive influence on the benefits of bioenergy ($\beta = 0.430$; $p \leq 0.001$). This is because the population is becoming more aware and aspires to higher levels of sustainability, especially due to their experiences with the health problems generated by smoke inhalation, the loss of opportunities, the evidently increasing deforestation, the loss of plant and animal species, and associated traditional knowledge.

H4 is rejected. Costs have a negative influence on bioenergy capabilities ($\beta = 0.313$; $p \leq 0.001$). This situation can be explained by the fact that the program offers support for trainers, training in the communities themselves, and biodigesters for community use, which has permeated the perception of the communities. Therefore, the costs may not be perceived as unfavorable for the implementation of bioenergy.

H5 is rejected. Capabilities have a positive influence on the benefits of bioenergy. Bioenergy capability has a negative influence on bioenergy benefits ($\beta = -0.159$; $p \leq 0.05$). The results show that people have not been able to link the benefits that capacities can generate in environmental matters.

Discussion

San Agustin de los Tordos and El Comedero Grande, the communities with which we are engaged in this research, have confirmed that energy expenditure exceeds 10% of their income, a situation that is particularly acute in households led by women. This high energy cost has repercussions on access to essential goods and services, including basic food, education, and healthcare. Additionally, it limits recreational activities, reduces personal time, and family interactions and exposes individuals to various risks, such as injuries while collecting firewood and health issues from smoke inhalation. These circumstances classify the San Agustín de los Tordos and El Comedero communities as experiencing energy poverty.

This research offers a quantitative study aimed at gaining a deeper understanding of how bioenergy is implemented in communities in the global south. It explores the relationships between compensatory alternatives, capacities, costs, and the perceived benefits of implementing bioenergy. However, to fully comprehend energy scarcity as a facet of social injustice, it is imperative to generate qualitative data. Qualitative information can provide a more holistic understanding of the socio-technological–ecological system, shedding light on the potential benefits of bioenergy for the system's sustainability [48].

A holistic perspective derived from socioecological systems aids in better understanding the energy issue. The analysis presented in this research underscores that, in the face of evident energy shortages and economic constraints, rural communities have developed compensatory alternatives. These alternatives include cost-saving measures, reliance on natural light and heat, and the use of firewood for combustion. While these compensatory alternatives may reduce short-term energy needs, they carry negative consequences for health, demand significant time and effort, harm the natural environment through deforestation, soil erosion, and displacement of wildlife and even lead to cultural losses. Over time, these alternatives can transform into socioecological traps.

Conducting research that delves deeper into the generation of these traps within specific contexts and identifying alternative energy system models is vital. However, the scarcity of multidisciplinary research addressing energy issues remains a significant challenge for academic endeavors focused on energy system analysis. While efforts like the one presented in this work contribute to the body of knowledge, they alone cannot fully address the issue of energy poverty.

In addition to understanding perceptions and capacities within communities, various other factors, such as public policies, structural conditions, the economic system, and more, exert influence on the development of energy systems in specific locations. These elements play a pivotal role in shaping the trajectory of energy systems, determining whether they evolve positively, or otherwise, within a given area.

Conclusions

This study reveals that energy alternatives used by the communities of San Agustin de los Tordos and El Comedero Grande operate as socioecological traps, negatively affecting bioenergy capability. However, at this stage, these alternatives still provide benefits that offset the costs of implementing bioenergy. This suggests that the system is currently well positioned for the development of new capabilities. The absence of a positive and significant relationship between bioenergy capacity and its benefits highlights an opportunity for this project. There is a need for a clearer demonstration of the environmental benefits of bioenergy and a focus on other benefits, such as social, economic, and opportunities associated with its adoption.

The recommendations from this research emphasize leveraging the current phase of these communities. This involves strengthening their existing capabilities through technical elements, workshops, and training programs that address the energy problem from a socioecological perspective and explore the multifaceted benefits of bioenergy for the population. It is important to recognize that human activity within a socioecological system involves complex interactions between social and natural components.

Additionally, it is essential to acknowledge that, while communities do perceive some benefits from bioenergy, these advantages are not yet significant in economic and social terms. Bioenergy and rural development are closely linked, even though these processes may not yield immediate results.

By using a measurement model and validating it through observed positive correlations among variables such as compensatory alternatives, bioenergy costs, and bioenergetic capacity, we can facilitate the transition to sustainable energy solutions for the communities of San Agustin de los Tordos and El Comedero Grande. While this research relies on quantitative methodologies, future studies should consider exploring qualitative data, particularly through participatory action research, to further enhance positive influences within these communities.

Appendix 1
Questionnaire in Spanish

Variable: Alternativas de compensación	
Hemos implementado estas acciones para compensar nuestras necesidades de energía	
1 = completamente en desacuerdo	
2 = en desacuerdo	
3 = ni en descuerdo ni de acuerdo	
4 = de acuerdo	
5 = completamente de acuerdo	
COMP1	Uso de focos ahorradores
COMP2	Aparatos de uso eficiente
COMP3	Disminuir el consumo de electricidad
COMP4	Disminuir el consumo de gas
COMP5	Disminuir la compra de leña y carbón
COMP6	Conseguir ingresos extras
COMP7	Recolectar leña
COMP8	Aprovechar luz natural
COMP9	Aprovechar calor natural
Variable: Costos de la bioenergía *Este aspecto nos presenta una dificultad para la implementación de la bioenergía*	
1 = completamente en desacuerdo	
2 = en desacuerdo	
3 = ni en descuerdo ni de acuerdo	
4 = de acuerdo	
5 = completamente de acuerdo	
EDBIO1	Costo económico
EDBIO2	Dificultad para adquirir nuevos conocimientos
EDBIO3	Falta de tiempo
EDBIO4	Escasez de capacitadores
Variable: Capacidad de bioenergía *Hemos desarrollado este aspecto de la bioenergía*	
1 = completamente en desacuerdo	
2 = en desacuerdo	
3 = ni en descuerdo ni de acuerdo	
4 = de acuerdo	
5 = completamente de acuerdo	
EOBIO1	Reconocimiento de la necesidad de implementación de bioenergía
EOBIO2	Interés en la implementación de bioenergía
EOBIO3	Conocimiento previos en el uso de biomasa
EOBIO4	Experiencias anteriores con el uso de biomasa
EOBIO5	Aceptación de la nueva forma de aprovechamiento de la biomasa
Variable: Beneficios de la bioenergía *La implementación de la bioenergía puede generar los siguientes beneficios:*	
RBIO1	Tiempo libre
RBIO2	Tiempo con la familia
RBIO3	Relación con la naturaleza, flora del lugar
RBIO4	Conservar recursos naturales
RBIO5	Mejor relación con la naturaleza
RBIO6	Conservar recursos naturales del lugar

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Author contributions
M.R.R.S. designed the study and wrote the first version of the paper. A.M.M.O. helped in design and analysis of results. V.O.P. revised analysis and methodology. M.H.R. supervised the study and wrote the final version of the paper. All authors revised the final version of the paper.

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Declarations

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The authors have no competing interests to declare that are relevant to the content of this article.

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