Designing renewable and socially accepted energy systems for astronomical telescopes: A move towards energy justice

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Abstract

Remote astronomical telescopes without access to the national electricity grid rely mostly on fossil fuels. Climate change concerns and fuel price vulnerability drive the transition to renewable energy sources. Astronomical facilities are usually designed without considering the surrounding communities' social and energy needs or using renewable energy sources to power them. This study proposes a socially accepted renewable energy system for a future telescope in the Atacama Desert, combining an energy system model with a participatory multi-criteria analysis. Our findings highlight that various stakeholders prioritize emission reduction, security of supply, and electricity costs. The results reveal that a renewable energy system supplying the telescope could also cover 66% of the nearby San Pedro de Atacama community's energy needs without additional capacity. Replicating similar energy systems at nearby telescopes could reduce fossil fuel-based energy generation by over 30GWh annually, cutting emissions of the area by 17-23ktCO_2eq, while contributing to energy justice.

Introduction

As Plato said already 2500 years ago "Astronomy compels the soul to look upwards and leads us from this world to another": today astronomy can redeem his quote leading by example in the urgent transition to a new net-zero world keeping our planet inhabitable. Ground-based telescopes are typically built in remote, high, and dry places, necessary to minimize water vapor in the atmosphere, which affects observations. One of the global astronomical prime spots is the Chajnantor plateau in the Atacama desert, Chile. Today this site, with altitudes between 3,500 and 5,200 meters above sea level (m.a.s.l.), is home to more than ten international observatories, including the Atacama Pathfinder Experiment (APEX) and the Atacama Large Millimeter/submillimeter Array (ALMA). Due to their location, astronomical facilities are often not connected to the national electricity grid and rely on individual diesel and gas generators to supply their power-intensive operations. These include cryogenic cooling for instruments and movements of the telescope structure while it points and tracks the astronomical targets. To guarantee that the astronomical instruments are constantly cooled, power outages must be prevented. Concurrently, increasing fuel prices and climate change concerns incite telescope operators to uptake renewable energy sources (RES) in their energy supply and reduce their dependence on fossil fuels.

The astronomical community is active in proposing solutions to reduce its carbon footprint. Starting in 2020, Stevens et al. discussed the "imperative to reduce carbon emissions in astronomy" [1, p. 843]. suggesting the necessity of investing in renewable technologies and reducing air travels of astronomers. Burtscher et al., in 2021, strongly argued in favor of reducing flights for astronomers by replacing them with other means of transport and virtual meetings [2].

Some telescopes recently took action toward integrating RES into their facility. For example, La Silla observatory has been powered by more than 50% from solar energy since 2016, while in 2022, the Very Large Telescope and the Extremely Large Telescope in Chile together commissioned a 9MW photovoltaic (PV) park to avoid 1,700 tons of CO_2-equivalents (CO_2eq) emitted per year [3], [4]. The new telescope "Atacama Large Aperture Submillimeter Telescope" (AtLAST), planned on Chajnantor, is the first observatory including RES already in its design stage [5], [6].

While CO_2eq emissions from the astronomic sector are increasingly studied and discussed, the considerations of energy justice, including the social impact on local communities, of the astronomical infrastructures are of high importance and need to be addressed in the debate and research. Due to the advantageous geographic conditions of the Atacama desert, investments in astronomical observations are expected to grow in this region representing around 70% of the global observation capacity and above 90% of the investments made in the Southern hemisphere by 2025 [7]. As the hosting country for many astronomical facilities including those developed and operated by the European Southern Observatory (ESO), Chile takes a leading role in global technological and scientific advancement while being responsible for protecting and enhancing the conditions for local communities. As a result, astronomical observations can serve as leverage for the region's development and a mean for international exertion of influence at the cost of local benefits [8].

Distant 50km from the Chajnantor plateau, San Pedro de Atacama (SPA) is located at an altitude of 2,400 m.a.s.l.. With a stable population of around 11,000 people (2017) [9], its main economic activity is tourism, mainly accommodation and food services, which adds an extra floating population of 14,000 people per typical year. Since the national electricity grid ends 100km from this community, the town is mainly supplied by the local utility, Cooperativa Eléctrica San Pedro de Atacama (CESPA), operating solely diesel and natural gas generators until 2022. Unlike the telescopes, SPA's energy consumers suffer frequent power outages. Subsequently, some higher-end hotels run their own diesel generators and PV. CESPA's electricity prices range higher than the national average [10].

Apart from designing a RES system for the new telescope, the project AtLAST aims to examine different scenarios to provide electricity also to the local community of SPA, under consideration of the objectives of affected and affecting stakeholders. Previous studies have shown that involving stakeholders at an early stage of a renewable energy project and considering their objectives in the evaluation and decision-making processes have implications for the degree of energy justice of the proposed project design [11]–[13].

Therefore, this study applied a participatory Multi-Criteria Analysis (specifically the Multi-Actor Multi-Criteria Analysis (MAMCA) [14]) to incorporate both the technical performance, as well as the social preferences in the evaluation of different energy scenarios. Building on combined approaches in previous studies on energy communities in the European Union [15], [16], this study was embedded in larger engagement activities, including the conduction of surveys, interviews, and communal workshops. The quantitative and qualitative data generated through these activities and a mixed-integer linear program (MILP) model used for the energy system optimization were fed into MAMCA. Figure 1 presents a summary of MAMCA steps and its main results, starting with the consultation with the stakeholders about their preferences on the creation of energy communities in SPA, followed by the definition of different energy scenarios and then cost-optimized in the next step, and finalizing with the realization on in-site workshops to capture the stakeholders' opinions of these energy scenarios, resulting in the determination of a scenario ranking.

In this article, we study the design of a renewable energy system for the future AtLAST on the Chajnantor plateau, considering the involvement of the local community of SPA. We answer the research question: How can energy systems for astronomical telescopes become renewable-based and inclusive? The answer to this question can also guide the planning of other remote infrastructure projects.

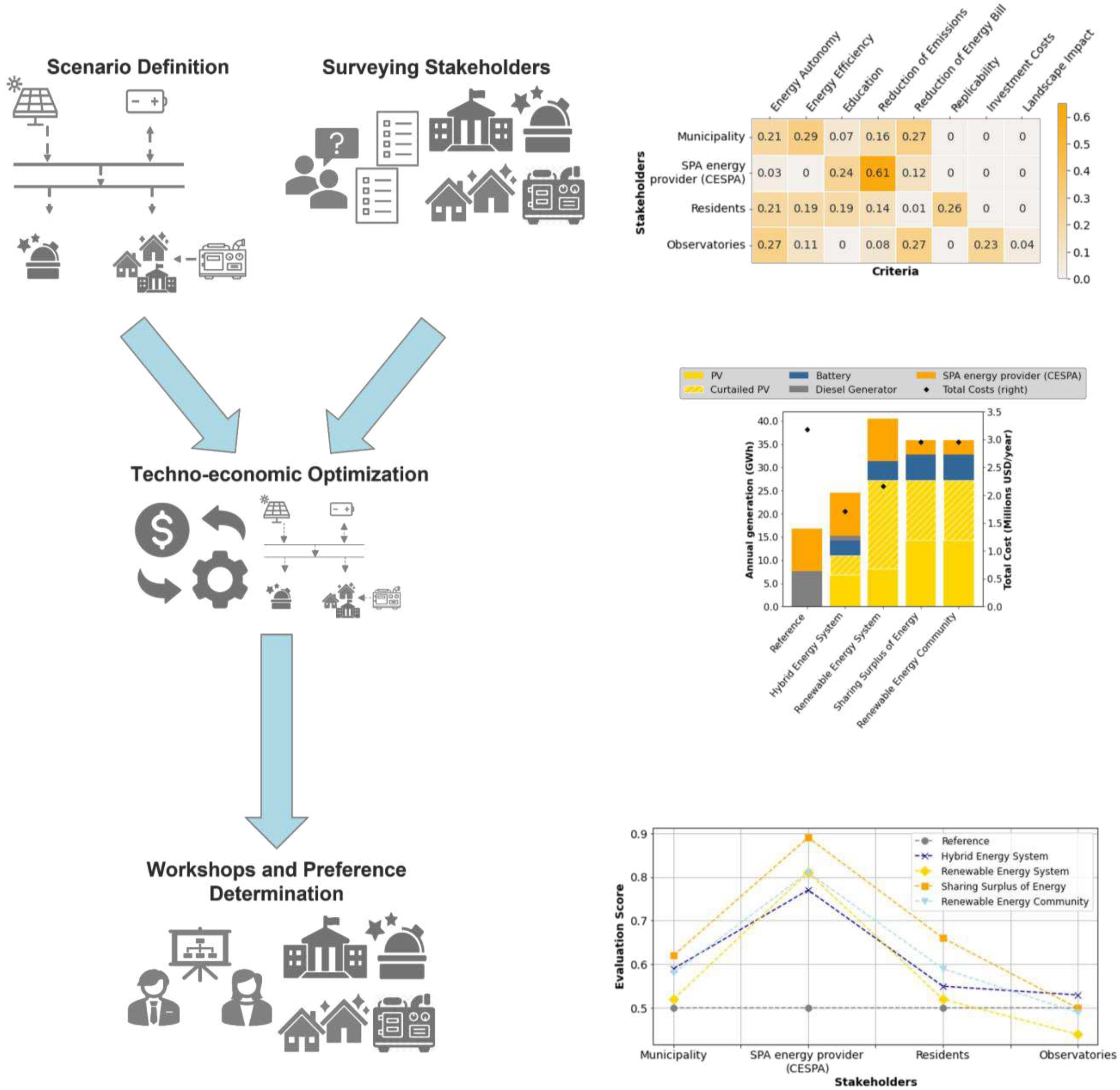

Figure 1: Summary of MAMCA methodology and its main results obtained for the present study.

Results and discussion

Stakeholder perspectives and barriers towards renewable energy systems in San Pedro de Atacama: assessing criteria and challenges

As an initial step of the research, we conducted a survey to assess the affected and affecting stakeholders and their corresponding criteria (see more details of the survey in the Supplementary information section "Survey"). The identified stakeholders were the municipality, residents of SPA, representatives of the local energy provider (CESPA), and some observatories hosted in the

Chajnantor plateau (e.g. ALMA, APEX, Simons Observatory, among others). Based on the survey results, different stakeholder groups identified various criteria as most important and assigned different levels of importance to those criteria during the workshop (see Figure 2). For example, the participating residents considered the system's replicability (similar system configurations can be implemented in surrounding villages) the most important criterion. CESPA prioritized the reduction of CO_2eq emissions, the municipality focused on increasing energy efficiency, and the observatories emphasized energy autonomy and electricity cost. Additional objectives that were mentioned by stakeholders included education on energy matters, energy efficiency, and energy autonomy.

Summarizing the importance scores of the different stakeholder groups, we obtained that the reduction of emissions, the autonomy of the system, and the reduction of the energy bill were the most important criteria for the affected stakeholders. Conversely, landscape impact received less importance and was only considered by the observatories.

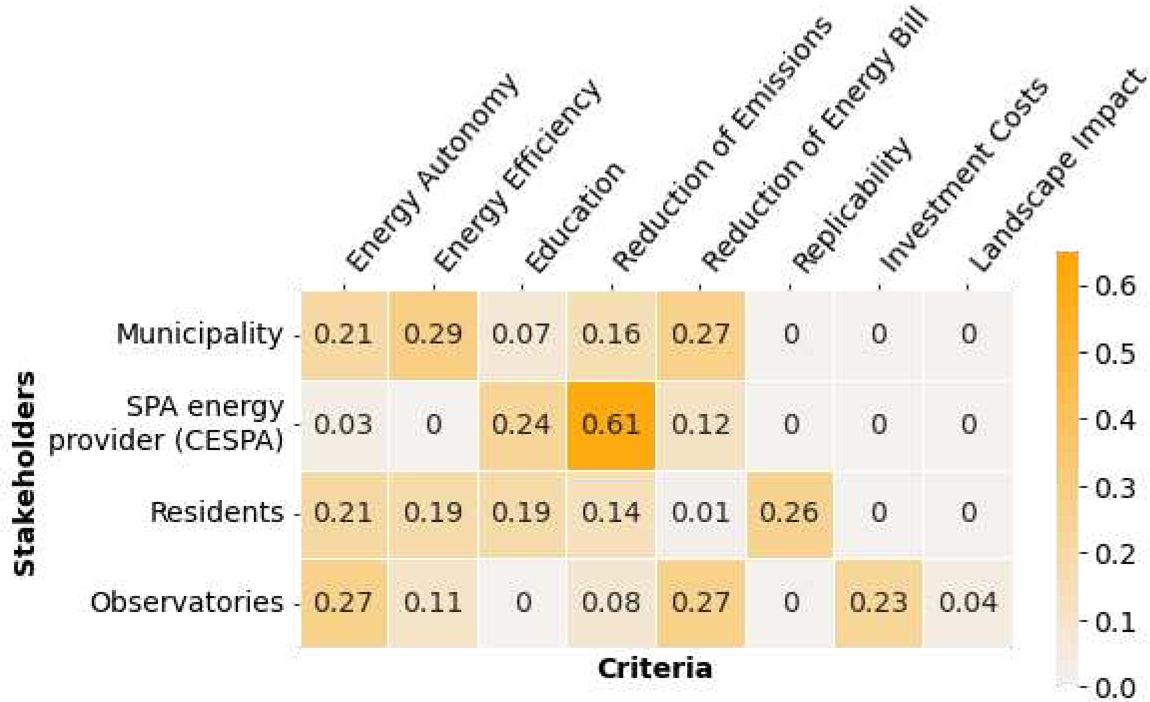

Figure 2: Stakeholders' weighted criteria according to the survey.

Furthermore, the survey aimed to gather insights on the challenges and barriers towards RES systems in SPA. Respondents identified several aspects, such as the lack of collaboration between the indigenous and the non-native population of SPA as well as between the local communities and the national electricity grid. Respecting indigenous land was also emphasized as crucial consideration. Another barrier highlighted was the long distances between energy generation sites and consumers because some villages in the surroundings of SPA, such as Toconao, Socaire, Peine, and Camar, are not connected to CESPA's grid, and would require the installation of distribution lines. In addition, residents expressed concerns regarding the responsibilities associated with the ownership of individual generation assets like PVs, referring to maintenance and operating costs. The municipality of SPA further identified challenges to the large-scale implementation of alternative energy system solutions, including public acceptance, high investment costs, and lengthy legal and regulatory procedures.

Finding synergies: inclusion of the communities in the energy planning process

Following the initial MAMCA stage of surveying stakeholders and their objectives, four scenarios to include RES for the telescope and the community were drafted, in addition to a reference scenario. The surveys unraveled the respondents' desire to use RES, the telescope operators' need for continuous energy supply, and the wish for cheaper electricity costs.

Following the idea of energy communities, five scenarios supporting the telescope's and SPA's energy needs were considered (see also Table 1 in Methods).

1. A system supplying AtLAST solely by diesel generators, similar to today's powering of other telescopes in the area, serves as the *Reference* scenario.
2. The *Hybrid Energy System* proposes to supply the demand of AtLAST, 7.7GWh/year, with PV, batteries, and diesel;
3. The *Renewable Energy System* supplies AtLAST's demand with solely PV and batteries;
4. *Sharing Surplus of Energy* expands the *Renewable Energy System* (scenario 3) so that the surplus energy not used by AtLAST is supplied to the local community in SPA;
5. *Renewable Energy Community* integrates a system using PV and batteries to cover the entire demand of AtLAST and part of the town's energy demand by sharing energy with them. In this scenario, AtLAST, the SPA energy provider (based on diesel generation), and the SPA community are included in the decisions about the system, unlike in the previous setup (scenario 4), where only AtLAST was involved in the decisions.

In the first three scenarios, we assume that CESPA, the energy provider in SPA, meets the community's energy demand solely through diesel generation. However, in the last two scenarios, the demand can be met by both CESPA and energy sharing.

By integrating the communities in the planning process, options for synergies became apparent, which included the opportunity to use surplus energy from the telescope's energy system to fuel the SPA community, otherwise curtailed. Hence, the idea of integrating RES into the design of AtLAST can introduce the astronomical community up on the Chajnantor plateau and on the nearby residential areas to more sustainable energy systems.

This idea of creating synergetic usage of the RES energy system follows the concept of energy communities, a union of different entities (public, private, commercial) that jointly invests in or share energy infrastructure or provide energy services and builds on open and fair decision-making [17]. Distributing benefits to multiple stakeholders through an energy community can lead to a more socially accepted energy transition.

Optimizing energy system scenarios for AtLAST and San Pedro de Atacama: renewable energy integration and cooperative solutions

Following the survey and scenario definition, the five energy system scenarios were optimized using an energy system model to match the given annual energy demand of 7.7GWh/year for AtLAST and 9.76GWh/year for SPA with energy supply from PV, batteries, and/or diesel generators. Figure 3 shows the results obtained through the optimization of each energy scenario for AtLAST: the yellow, grey, and blue bars represent the annual generation of the energy system (Figure 3a) and its installed capacity (Figure 3b) per technology; and the dots (Figure 3a) represents the total cost obtained in each scenario. In addition, the SPA energy provider's diesel generation is represented in orange bars in Figure 3a to analyze the changes in energy supplied by CESPA to SPA in each scenario. Notably, the first three scenarios (*Reference*, *Hybrid Energy System*, and *Renewable Energy System*) focused solely on supplying electricity to the new telescope, while the last two (*Sharing Surplus of Energy* and *Renewable Energy Community*) explored cooperative solutions that also provided electricity to the SPA community.

The *Hybrid Energy System* proved to be the most cost-effective scenario, with a yearly total cost of $1.7 million, representing a 46% cost reduction compared to the *Reference* scenario. Moreover, the diesel generation in this scenario is reduced by 85%, but it still plays a significant role in meeting the electricity demand while not oversizing the PV and battery capacities like in the other scenarios with RES.

The *Renewable Energy System* emerged as the second most cost-effective scenario, with a total cost of $2.2 million per year, which meant an improvement of 32% compared to the *Reference* scenario. This case relied solely on PV and battery technologies, ensuring a 100% RES reliance. PV and battery capacities were significantly increased by 148% and 65%, respectively, compared to the *Hybrid Energy System* to compensate for nighttime and low solar irradiance periods. However, this led to a nearly four-fold increase in curtailment compared to the previous scenario.

In cooperative scenarios, the *Sharing Surplus of Energy* and the *Renewable Energy Community* showed a yearly total cost of $2.96 million, a 7% improvement compared to the *Reference* scenario. Though incurring higher costs than the two previous RES scenarios, these cooperative ones significantly reduced the fossil fuel consumption in the area. Sharing surplus energy with SPA covered 66% of the town’s electricity demand, reducing reliance on the local utility’s diesel generation, as illustrated by the orange bar in Figure 3a. Including the SPA community also contributed to a 33% reduction in curtailed PV energy compared to the *Renewable Energy Scenario*.

While the *Sharing Surplus of Energy* and *Renewable Energy Community* scenarios had identical installed capacities, energy generation, and shared energy with SPA, the former did not consider the existing utility system in the decision-making process of the energy system. In contrast, the *Renewable Energy Community* scenario involved CESPA in this process, resulting in a more inclusive energy system. Although the difference is techno-economically insignificant, the latter scenario facilitates a more inclusive energy system.

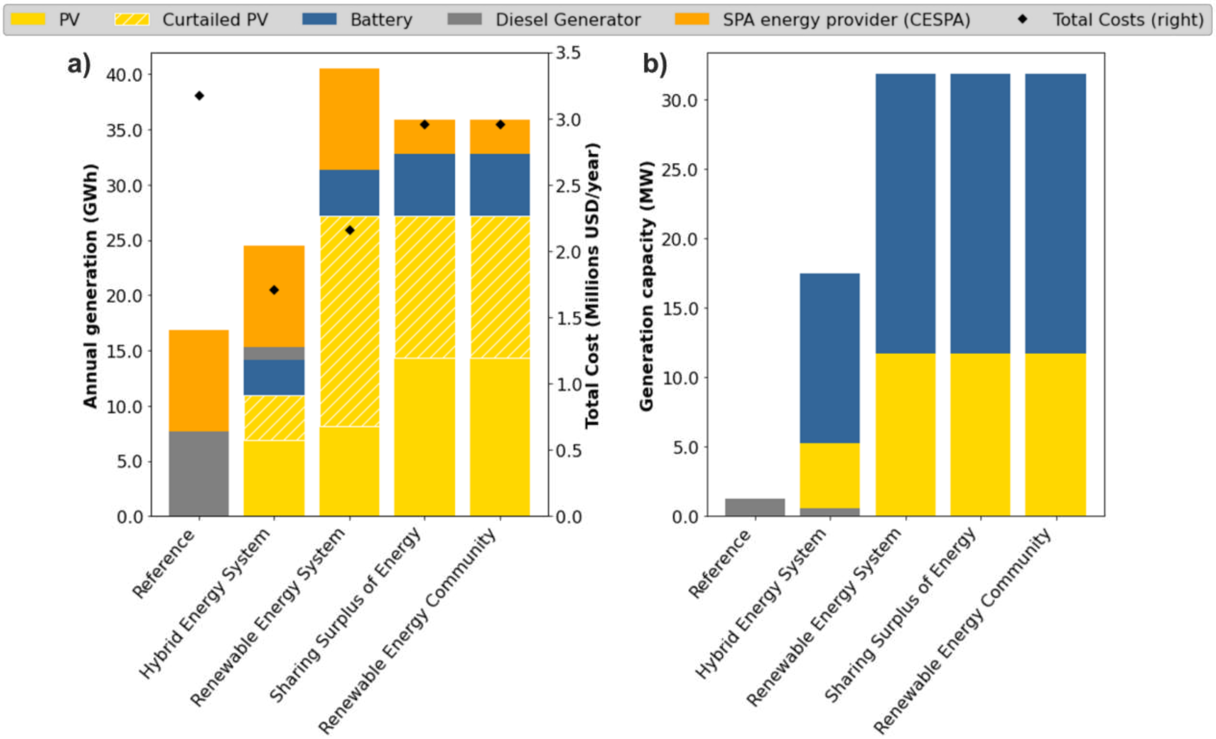

Figure 3: Comparison of annual generation of energy, total costs (Figure 3a), and modeled generation power capacity (Figure 3b) across the five scenarios. SPA energy provider's diesel generation is represented in orange in Figure 3a.

AtLAST requires a reliable electricity supply to prevent power outages and subsequent operational problems. Among the solutions considering RES, the *Hybrid Energy System* provides the most reliable alternative, as it considers diesel generation, not relying 100% on RES, which are affected by extreme weather events and may cause power outages. However, this scenario does not address the electricity demands of the surrounding SPA community or contribute to its decarbonization goals like the cooperative scenarios do. While the *Hybrid Energy System* may not promote social inclusivity regarding energy access, it offers a cost-effective and dependable energy solution for AtLAST.

In contrast, the cooperative scenarios differ from the *Hybrid Energy System* by involving the SPA community through the shared surplus generated by a 100% renewable energy system. However, this approach entails higher total costs and the potential for intermittent operation due to the reliance on RES. To mitigate the higher total costs, exploring agreements between the community and the AtLAST energy system, such as establishing a fixed price for the supplied electricity, could be considered. For instance, setting an electricity price of $180 per MWh consumed (current electricity price is $378 per MWh [10]) in the *Renewable Energy Community* scenario (equivalent to the cost of electricity consumed in the cooperative scenarios) and considering that the shared electricity amounts to 6,094.3MWh per year, AtLAST would generate an additional annual income of $1.1 million. This arrangement would effectively decrease the yearly total cost of this cooperative scenario to $1.9 million. Future research should focus on determining a fair price for the electricity supplied by AtLAST to the community, incorporating the perspectives of all stakeholders.

In conclusion, our findings indicate that a renewable energy system sized to supply AtLAST could also cover 66% of the electricity demand of SPA without additional further capacities in PV or battery capacities. This integration would reduce local reliance on fossil fuels. However, a 12km transmission line between the two locations would be necessary, incurring additional investment costs that would increase the total cost of the cooperative scenarios by the same amount.

Workshop insights: collaborative energy communities for a renewable energy system in San Pedro de Atacama and Chajnantor

Following the optimization findings, we conducted workshops with the identified stakeholders in SPA and some of the telescope operators to discuss the possibility of energy communities in the area. As shown in Figure 4, the stakeholders, except for the observatories, favored the *Sharing Surplus of Energy,* as it reduces CO_2eq emissions and electricity costs, two criteria that obtained significant importance in the survey. In contrast, the scenario relying solely on diesel received the lowest evaluation score, as stakeholders strongly favored an energy system capable of reducing CO_2eq emissions (more details of the evaluation scores in Supplementary Table 1).

The observatories were interested in systems including RES, though they preferred those with diesel backup, such as in the *Hybrid Energy System*, to ensure a reliable energy system. They showed reluctance towards systems relying on 100% RES since they could face intermittent issues (see Figure 4). This preference was reinforced by the absence of specific guidelines promoting using RES in astronomical telescopes to mitigate the sector's CO_2eq emissions. Within the 100% RES scenarios, the observatories rated the *Renewable Energy Community* scenario more favorably than the *Renewable Energy System*, as it reduces their investment costs by involving other stakeholders. In line with the previous results of the survey (see Figure 2), the observatories strongly prefer low electricity costs (reduction of energy bills and investment costs).

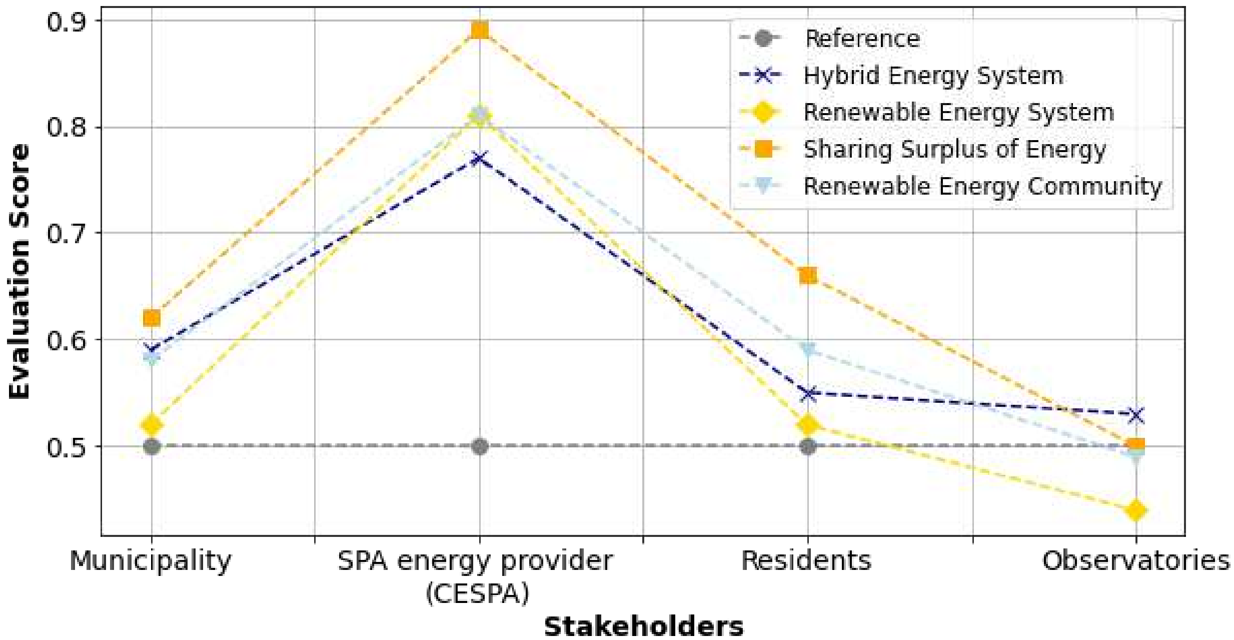

Figure 4: Preferences in energy system setup per stakeholder group, resulting from the discussion during the workshops.

The workshop highlighted the challenges faced by observatories in investing in RES due to their short-term budget planning horizon. For instance, APEX, at the time of the workshop in mid 2022, had secured funding from the Max Planck Institute for Radio Astronomy until the end of 2025. Operators voiced difficulties installing PV systems due to high initial CAPEX and a longer return on investment timeframe. As a result, CESPA and the observatory operators discussed potential cooperation during the workshop. CESPA, in the process of building its first PV park in mid of 2022 [10], showed interest in providing electricity to the telescopes on Chajnantor. The telescopes were eager to be supplied with reliable, affordable energy from RES by a third party, eliminating the need to manage their own power plants.

Considering this as an additional scenario, incorporating CESPA as the electricity supplier for the telescopes on Chajnantor could have several benefits for the SPA community and the area. Firstly, the inclusion of the other telescopes as consumers would help prevent the power outages currently experienced by the SPA community. Since the telescopes require a reliable energy system, CESPA would need to ensure that they install sufficient power capacity to meet the needs of all their customers, including the SPA community. Secondly, CESPA's plans involving RES would contribute to reducing the current emissions at Chajnantor. Ground-based telescopes, relying on fossil fuel generators, emit an average of 24tCO_2eq per research paper, as reported by Knödlseder et al. [18]. Based on our estimation, the telescopes on Chajnantor, with an annual energy demand of over 30GWh, currently emit approximately 17-23kt CO_2eq per year. If CESPA were to supply electricity to all the telescopes using RES, the emission amount would decrease significantly, thereby making a valuable contribution to mitigating CO_2eq emissions. Further investigation should be conducted to explore the scenario where CESPA installs sufficient PV and storage capacity to supply both SPA and most of the telescopes up on Chajnantor.

Localizing benefits of the growing sector of astronomical observations by including energy justice

The Atacama Desert is a prime location for solar energy projects, holding the maximum global solar irradiation maximum [19]. Over the last decade, solar projects in the Atacama surged to power lithium mines and export energy to other provinces. However, distributional issues arise as the Atacama hosts 85% of the solar energy developments in the country [20], while Atacameños pay more for their energy than the demanders in the capital region. A household with a demand of 650kWh per month in 2022 had to pay 0.165$/kWh in Santiago, Chile's capital, compared to consumers in Antofagasta paying 0.184$/kWh (utility Elecda), 0.222$/kWh (utility Saesa) and 0.378$/kWh in SPA (utility CESPA) [10], [21]. Therefore, decisions regarding the energy supply to telescopes that consider and mitigate potential negative impacts on local communities have a major influence on the level of energy justice of the renewable energy system designed for the AtLAST project.

Energy justice addresses questions such as how decisions concerning energy generation are taken, whose perspectives and objectives are considered, how costs and benefits are distributed, and where injustices occur(ed) (temporal, local, regional, and global) [22]. Sovacool traces the concept back to Rawls' classical Justice as fairness and highlights its importance because "how we distribute the benefits and burdens of energy systems is pre-eminently a concern for any society that aspires to be fair" [23, p. 15].

Calzadilla and Mauger examined several energy injustices in the Atacama region, the exclusion of local populations in the development of solar projects, and the limited offer of jobs to very few, highly educated individuals [20], often commuting from the capital region. Furthermore, large-scale solar projects in the Atacama suffered from a lack of democracy. Developments so far were accompanied by a "weak information and participation process" [20, p. 250], with local opposition receiving low priority from investors in RES. Excluding local stakeholders in decision processes is a source of procedural energy injustices and has major implications on other aspects of energy justice, such as the lack of shared benefits, the disregard of the needs and lived reality of local communities, and their disproportionation exposure to landscape impacts including local pollution and over a long time horizon [11].

By engaging local communities in participatory decision-making (e.g., by applying MAMCA), procedural and recognition justice considerations can be represented and considered in the design and development of new large-scale energy projects. The participation of the stakeholders in the survey and the community workshops showed that the local community aligns with the objectives concerning their energy supply (affordability, reduced emissions) with the main investing stakeholders (AtLAST) but stressed additional aspects such as the replicability of the system in surrounding communities and barriers to their implementation.

In discussions with stakeholders, future areas of research evolved. Telescope operators raised the question of the scope of lifecycle CO_2eq emissions of the *Renewable Energy System* compared to the *Hybrid Energy System*. Aligning with restorative energy justice considerations, which require integrating impacts along the installed technologies' entire life cycle (from sourcing to waste management), the present study can be extended by conducting a life cycle assessment. With this, the three main pillars of sustainability: environmental, social, and economic implications could be considered within the energy system design of AtLAST.

The community workshops provided a platform to explain different renewable energy system designs and their impacts on the stated objectives of the stakeholders. The collaboration of the different participating stakeholders generated feedback to improve the scenarios. MAMCA served as a structured participatory approach tool to capture different types of objectives in the energy system design. As a result of the approach and taking into consideration energy justice aspects, integrating benefit sharing across the different stakeholders became central to the discussion and preferred solution.

Methods

A combined approach of participatory Multi-Criteria Analysis and energy system modeling

For the guiding methodology to evaluate the different scenarios of the energy system of the AtLAST telescope, we applied MAMCA [14]. The typical elements of MAMCA, namely scenarios, stakeholders, criteria, and evaluation, were supported with additional methods, which are shown in Figure 5.

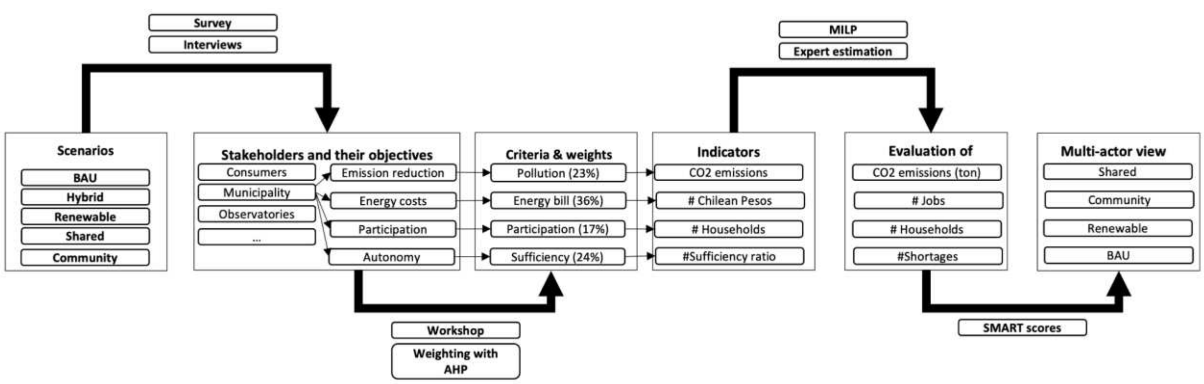

Figure 5: Six steps of the MAMCA method applied, from scenario building to multi-actor view.

In the first step, the feasible energy system scenarios were defined in discussions between the researchers and observatory representatives. Local stakeholders were involved through a survey (see the Supplementary Information section “Survey” for more details on the questionnaire). In addition, unstructured interviews were conducted with the municipality. The survey contained questions to assess the stakeholder’s objectives concerning their energy supply, perceived barriers to their implementation, and a snowball method question to identify affected and affecting stakeholders.

The results were included in the communal workshops, during which the selected objectives were confirmed and weighted using the pairwise comparison Analytic Hierarchy Process (AHP) [24]. Then, the optimization results of the MILP were used to allocate evaluation scores for the derived indicators assessing the performance of the criteria in the scenarios. Lastly, a ranked overview of the scenarios was compiled for each participating stakeholder group using the weight scores of AHP and the Simple Multi-Attribute Rating Technique (SMART) [25] performance scores.

Mixed-integer linear program and scenario choice

Five scenarios for energy system setups were considered in the energy system modeling (see Table 1). The scenarios are constructed from the telescope perspective: the first three, which consider only its demand, are useful to analyze the trade-off between investment in RES and emissions reduction. The results of these first scenarios show that a system fully powered by RES causes a large amount of curtailed energy. To avoid this waste of energy, two additional scenarios were added, including the nearby community of SPA and its electricity demand. The first of these two additional scenarios evaluates the quantity of curtailed energy that can be absorbed by SPA's demand from the renewable energy system design for the telescope only. The second one considers the electricity needs of SPA already in the optimization and investment process. In both of these last two scenarios, the demand of the community that cannot be satisfied thanks to the telescope energy system is still provided by the local energy provider CESPA, which runs on diesel generators. These were assessed using a techno-economic optimization model, following a MILP. It optimizes the sizes of the PV plant, diesel generator, and battery storage system and their operation towards the minimum final costs, that is, annualized investment and operation costs, given the defined energy system components and involved consumers. The model follows an energy balance modeling approach, meaning that the supply must satisfy energy demand at any given moment. The technologies that supply energy are subjected to their own constraints, which include energy conversion equations, maximum sizes allowed, minimum partial-load, maximum energy outputs, and storage continuity. See [26] for a detailed description of the optimization model and [27] an application of the model to a case study including PV, diesel generators, and battery storage systems, similar to this case study. Component costs and demand of AtLAST are following our previous investigation [28].

Since the planned start of AtLAST's operation is in 2030, we considered this year for the techno-economical optimization of the five scenarios. For the 2030 demand of SPA, we increase the town's reported 2020 demand curves by the expected energy demand growth rate in Antofagasta [10], [29]. As the town mainly consists of residential and commercial demanders, the joint growth rate of these two sectors of 22% until 2030 was applied.

Table 1: Overview of scenarios of the Chajnantor and SPA area.

Scenario	**Involved consumers**	**Energy system components**	**Total consumption**
Reference	AtLAST telescope is supplied by an individual energy system. SPA uses its current energy system.	Diesel generators	7.7GWh/year (AtLAST)
Hybrid energy system	AtLAST meets its electricity demand with an individual energy system. SPA continues using its current energy system.	Diesel generators, photovoltaics, and batteries	7.7GWh/year (AtLAST)
Renewable energy system	AtLAST meets its electricity demand with an individual energy system. SPA continues using its current energy system.	Photovoltaics and batteries	7.7GWh/year (AtLAST)
Sharing surplus of energy	AtLAST telescope meets its electricity demand with a renewable energy system and shares the surplus generated by photovoltaics with SPA, which continues using its current energy system (CESPA).	Photovoltaics, batteries, and CESPA	17.46GWh/year = 7.7GWh/year (AtLAST) + 9.76GWh/year (SPA)
Renewable energy community	Shared renewable energy system between AtLAST and SPA, which is still connected to CESPA.	Photovoltaics, batteries, and CESPA	17.46GWh/year = 7.7GWh/year (AtLAST) + 9.76GWh/year (SPA)

Supplementary information

Survey

Welcome to this short survey about Renewable Energy Communities!
With the support of the University of Oslo, the University of Brussels is working on a project titled RENAISSANCE to support the development of a Renewable Energy Community at San Pedro and with its neighbouring communities .
The primary objective of the project is to develop Energy Communities with environmental, economic and social benefits to its members. Our proposal would involve the generation of renewable energy by the community and for the community in a truly cooperative manner.
As a first step, we would like to get inputs from community members on what you would see as the most relevant objectives concerning the energy you consume. This survey is research-driven. We, therefore, invite you to support us in filling out this survey. The survey will take about 8 minutes to complete.
Thank you in advance for your support!

Disclaimer

In addition to your opinion, we will collect some personal information such as age, education, employment condition linked to your email address, to be able to contact you for follow up, if needed. We securely store this data until the end of the research period. We respect your trust and privacy; therefore, we will never share this data with any third parties. Your personal data will be processed in accordance with the principles of the European General Data Protection Regulation (GDPR), in force since the 25th of May 2018 and the Chilean law on the protection of the private life (Number 19628, updated and in force since 2020). If you have further questions on how your data is processed you can always contact the Data Protection Officer by emailing [].
Have you read the text and agree taking part in the survey?

I have read it and agree
I disagree

Introduction

What are Energy Communities?

Energy Communities are a means to organise and unite citizens to become active participants in the energy market. Energy communities can pursue and fulfil different activities ranging from local renewable energy generation, over collective energy consumption, sharing and/or selling electricity to providing flexibility services through demand-response and energy storage provision. In that way, Energy Communities aim to provide direct benefits to citizens and energy end-consumers by, for example, cutting the electricity costs and greenhouse gas emissions while increasing renewable energy consumption and production through participation.

Q1 The answer to the following question is the perspective from which you fill out the survey. Please indicate which role do you have in the energy system:

a consumer (residential household)
a consumer (micro enterprise, 0-9 employees)
a consumer (small enterprise, 10-25 employees)
a consumer (medium enterprise, 25-200 employees)
a consumer (big enterprise, 200+ employees)
a consumer that both consumes and generates energy (prosumer) -residential
a consumer that both consumes and generates energy (prosumer) - enterprise
representative of "Cooperativa Eléctrica San Pedro de Atacama" (CESPA)
the municipality
an energy advisor
Other? Please specify clearly

Q2 Please rank (drag and drop) which aspects affect your decision to join an energy community initiative most (from 1 being most influential to 5 being least influential). If you use the paper version, please write down the numbers

Environment (e.g., emissions)
Economy (e.g., savings, costs)
Technical (e.g., guaranteed energy supply and production)
Social (e.g., shared benefits, collaboration)
Institutional/Legal (e.g., availability of support)

Q3 ***What are the most relevant objectives for you concerning your energy supply and production*****?**

	Not relevant	Relevant	Really relevant	Not Applicable/ I do not understand it
Emissions reductions (less fossil fuel emissions)				
Landscape impacts (e.g., change of build environment, noise)				
Return on investment (costs are proportional to the financial gains)				
Affordable investment and maintenance costs (installation, management and maintenance are within a reasonable price range)				
Lower energy bill (reducing the overall energy expenses)				
Replicability (the same system, products, business models can be upscaled)				
Innovation (pioneering in new techniques and systems)				
Employment (creation of additional jobs)				
Commercial validation of products and services (being able to offer your own energy-related products and services)				

(Green) image building (product/service is perceived as more sustainable and green)	
Improve energy efficiency (e.g. reduce energy consumption by better management and more efficient equipment)	
Grid stability, continuity and reliability (avoiding power outages and electricity failures)	
Security (data protection and protection against cyber attacks, or other rogue actions)	
Energy autonomy (to have access to energy even when the main grid has an outage)	
Inclusiveness (incorporating social costs and a contribution for the socially weak for a just transition)	
Behaviour change (adopting a more sustainable and efficient use of energy in all aspects of our daily life)	
Education (more knowledge about sustainable energy and consumption)	
Available support (in form of available funds, information bureaus, facilitating policies and laws)	

Q4 Do you want to add other objectives that were not mentioned above?
Q5 Do you have any remarks on the questions?

Q6 Would you like to be part of a community that owns renewable energy assets (e.g., photovoltaic)?

Yes
No. Please explain why
I do not know

Q7 Which technologies would you like to have installed in that energy community? (multiple answers possible)

Photovoltaic
Wind turbines
Electric vehicles
Geothermal heat pumps
Biomass plant
Hydropower plant
Other?
None

Q8 What are/ can be challenges for you, San Pedro and the neighbouring communities to contribute to the energy transition?

Q9 Would you be willing to participate in a workshop on the topic of community energy?

Yes
No

Q10 If you want to stay updated and/or invited to the workshop, please provide us your email address:

Q11 What is your age?

18-25
26-35
35-55
55-69
70+
Prefer not to tell

Q12 From which village are you?

San Pedro
Toconao
Peine
Socaire
Camar
Talabre
Río Grande
Tocorpuri
El Laco
Paso Jama
Other? Please specify
Prefer not to tell

Q13 To which ayllus do you belong to?

Cuchabrache

Suchor
Bellavista
Guachar
Tambillo
Catarpe
Quitor
Conde Duque
Solcor
Yaye
Larache
Checar
Séquitor
Coyo
Tulor
Vilama
Solor
Cúcuter
Poconche
Beter
Other? Please specify:
Prefer not to tell

Q14 What is the highest level of education you have received?

Primary school
Secondary school
Professional/Technical training
University studies – “Bachillerato”
University studies (Bachelor degree)
University studies (Professional degree)
University studies (Master degree)
Doctoral degree
Preferer not to tell

Q15 In which range lies your monthly net income (CLP = Chilean pesos) ?

0 – 70 000 CLP
70 001 – 110 000 CLP
110 001 – 145 000 CLP
145 001 – 180 000 CLP
180 001 – 220 000 CLP
220 001 – 280 000 CLP
280 001 – 355 000 CLP
355 001 – 475 000 CLP
475 001 – 775 000 CLP
More than 775 000 CLP
Prefer not to tell

Q16 Which statement best describes your current employment status?

Working (paid permanent employee)
Working (self-employed)
Not working (retired)
Not working (searching for a job)
Not working (not searching for a job)
Prefer not to answer

Q17 In which sector do you work?

Industry
Observatory
Local government
Hospitality Industry (Hotel, restaurants, tourism)
Transport
Education
Energy
Others? Please specify

Q18 How do you identify?

Male
Female
Other
Prefer not to tell

Supplementary Table 1: Evaluation scores of scenarios.

Criteria	Scenario				
	Reference	**Hybrid energy system**	**Renewable energy system**	**Sharing surplus energy**	**Renewable energy community**
Landscape impact	5	4	3	3	3
Investment costs	5	3	1	1	2
Energy bill	5	7	6	8	8
Energy efficiency	5	4	2	3	3
Emissions	5	9	10	10	8
Energy autonomy	5	5	5	5	4
Education	5	5	5	7	9
Replicability	5	5	5	8	6

Abbreviations

AHP	Analytic Hierarchy Process
ALMA	Atacama Large Millimeter/submillimeter Array
APEX	Atacama Pathfinder Experiment
AtLAST	Atacama Large Aperture Submillimeter Telescope
CESPA	Cooperativa Eléctrica San Pedro de Atacama
ESO	European Southern Observatory
MAMCA	Multi-Actor Multi-Criteria Analysis
MILP	Mixed-integer linear programming
RES	Renewable Energy Sources
SMART	Simple Multi-Attribute Rating Technique
SPA	San Pedro de Atacama
PV	Photovoltaic

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