Designing a Hybrid Power System for a Remote Telescope in the Atacama Desert

Comparing microgrid optimizations with HOMER and GAMS

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***Abstract*—Chile, a country situated along the western coast of South America, is characterized by the presence of the driest desert in the world, the Atacama, which offers ideal conditions for astronomical observations. A new telescope is planned in the area, 120 km away from the last connection point of the Chilean power grid. Its power demand of 400 to 1,000 kW(el) is planned to be met with an islanded hybrid energy system. Whereas other observatories and villages in the area rely on diesel generation, the new telescope will be designed to be powered by renewable energy in combination with storage technologies.**

The costs and carbon footprint of the telescope's power infrastructure is investigated for scenarios: 1) A photovoltaic park in cooperation with diesel generators; 2) A photovoltaic park combined with a battery storage system; 3) Diesel generators. A year of operation is simulated both in HOMER and GAMS, calculating the consumed fossil fuels for scenario (1) and (2) and the size of the battery storage system necessary to allow operation. The results from the two simulation options are compared regarding their dimensioning, costs and direct carbon emissions. A sensitivity analysis for cost components is carried out.

Keywords- Microgrid; Photovoltaics; Hybrid energy system design; Carbon footprint

I. INTRODUCTION

Lowering the carbon footprint of scientific projects is crucial when science wants to contribute to keeping up with the Paris Agreement. In 2020, Stevens et al. [1] estimated the carbon emissions of Australian astronomers at 37 t CO_2e /yr. Next to greenhouse gas (GHG) emissions related to flights and the powering of supercomputers, more than 13% of this footprint stemmed from the operation of observatories. Telescopes need to supply power to substantial cooling units for their instruments next to the motors to track their dishes. For example, 57% of the Paranal Observatory's GHG emissions of 22,000 t CO_2e/yr in 2012 resulted from power generation with liquefied petroleum gas [2].

In consequence lowering GHG emissions is a significant factor when designing new telescopes, achievable amongst others by shifting to renewable energy (RE) systems. Some observatories subsequently added photovoltaic (PV) arrays, such as the Gemini Observatory in Hawaii, supplying 10% of its demand by PV since 2015 [3]. ESO's La Silla Observatory since 2016 is powered by more than 50% solar energy [4], [5].

The Atacama Large Aperture Submillimeter Telescope (AtLAST) is currently in its design phase [6], and is the first observatory project that includes plans for a RE system already at this stage. The Chajnantor plateau, where AtLAST will be built, is 120 km away from the last connection point to the Chilean power grid. Hence, an islanded power system solution, which includes RE-based technology and storage, is proposed.

The goal of this work is to discuss which costs and greenhouse gas emissions will incur in a hybrid energy system (HES) that uses:

1) A PV park combined with diesel generators;
2) A PV park combined with a battery storage system;
3) Diesel generators.

For this aim, islanded microgrid setups were optimized with both HOMER and GAMS which could supply the projected demand of the telescope and the nearby city San Pedro de Atacama.

II. METHODOLOGY

A. The energy system today

AtLAST is planned for a location high in the Atacama desert, at an elevation of approximately 5100-5400 meters above sea level, close to the telescopes Atacama Pathfinder Experiment (APEX) and the Atacama Large Millimeter/ submillimeter Array (ALMA). San Pedro de Atacama is the only city located in the vicinity, at 2400 m above sea level. Today, the telescopes' and the city's power systems are not connected. Each telescope has its power supplied separately by diesel generators close to them. The demand of San Pedro de Atacama, which consists of residential and small to medium commercial customers, is supplied by another diesel generation site closer to the city (called CESPA, as will be described in Section C).

B. Energy demand in 2030

To predict the power demand of the new telescope, the average and peak load of demand subsets like the cryogenic cooling of the instruments, the motors of the telescope and the electronics were taken into account. Since sub-mm telescopes like AtLAST can observe day and night, the power demand does not vary much throughout the day. Exemplary daily demand curves are shown in Fig. 1 (top).

The Chilean government expects the demand for power in the region to increase by 36.4% between 2020 and 2030 [7]. Applying this growth on today's demand of the municipality of San Pedro de Atacama results in typical daily patterns as shown in Fig 1 (bottom). Peak hours during the morning hours from 6 to 9 am and a higher demand in the evening can be seen here.

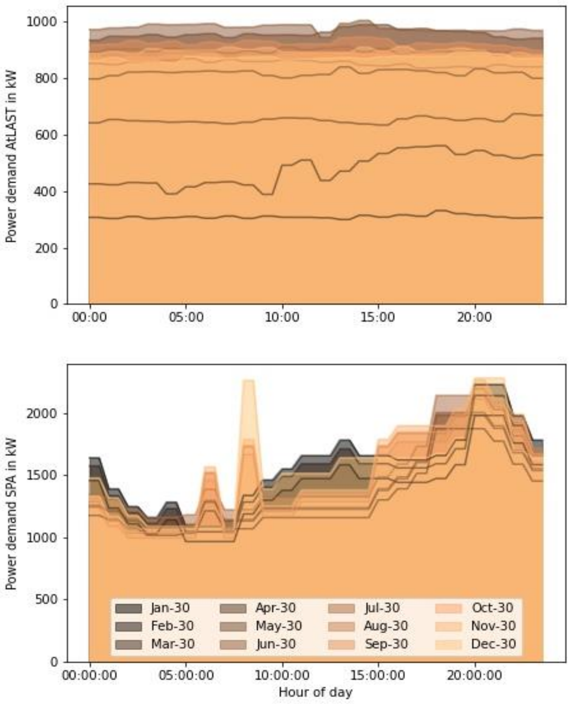

Figure 1. Typical daily demand patterns of AtLAST (top) and San Pedro de Atacama ("Site A") (bottom) in 2030.

C. Site description

Fig. 2 shows a map of the Chajnantor Plateau and San Pedro de Atacama area. The location of important sites for the presented hybrid power system are highlighted: San Pedro de Atacama ("SPA"), the current energy system of this city ("CESPA"), a selected site for the PV park and the battery storage system next to the gate of ALMA route, and one possible site for the new telescope on the Cerro Chico plateau ("AtLAST"). This site is used within this work, however different locations for the observatory on the Chajnantor plateau are investigated by the project and no final location has been set yet.

To reach the "AtLAST" site used in this work, one must pass through the ALMA gate located in "Site A" and then follow the corresponding route. The map in Fig. 2 indicates the distances between the points discussed. Note the length of the beeline from "AtLAST" to the other sites, which is almost four times the distance between any other two points. In addition, "CESPA", "SPA" and "Site A" are at an altitude of 2500 m, while the area of "AtLAST" is at an altitude of over 5000 m.

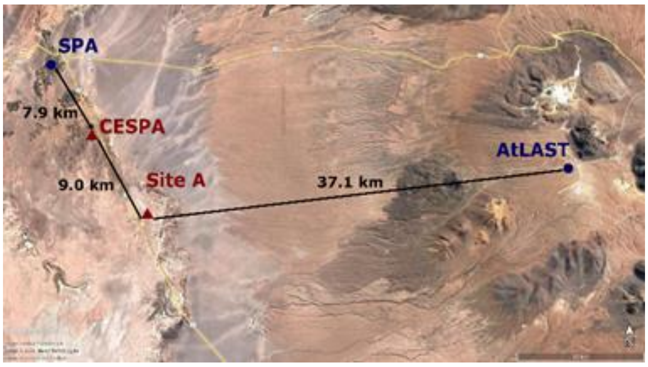

Figure 2. Map of the studied area, highlighting the AtLAST location used in this work next to other important sites for the design of the HES.

As CESPA currently uses diesel and natural gas generators to produce electricity for the local grid, we assumed that the new diesel generator considered in two of the scenarios will be located at the same site ("CESPA" in Fig. 2). For the PV park and the battery storage system, we selected an area located at the gate of the ALMA route ("Site A" in Fig. 2). This choice was based on a strategic decision to select the closest point to the current local energy grid of San Pedro de Atacama, on irradiation conditions discussed in the following section and on suitable environmental conditions (e.g. far from the open-sky mining sites near the astronomical park).

D. Weather conditions

The generation profile of a PV park depends on the Global Horizontal Irradiance (GHI), limiting the energy generation of a specific location. To obtain the generation profile of the selected site for the PV park (Site A), the Chilean online platform "Explorador Solar" [8] was used. This platform provides the necessary data to estimate the solar potential of a PV system based on i.a. its tracking module, tilt and azimuth. For this case, we assumed fixed monocrystalline and monofacial PV modules with a tilt of 23º and an azimuth of 0º (north).

Fig. 3 shows the annual global horizontal irradiation and monthly mean irradiation for "Site A" for the period from 2005 to 2016, where the lower value is registered for the year 2007 and the highest value for 2010. It is worth noting that the relative difference between both years is just 6%. Moreover, the monthly mean irradiation profiles for these years are similar: low irradiation during April-August (autumn and winter in Chile), and high values during January, February, October-December (spring and summer). Therefore, we select the worst year among this dataset (2007) to obtain a more robust solution.

Wind power generation was not considered for the present work, as the average wind speed in this area is very low (3.1 m/s) in comparison with other parts of Chile, where it reaches values between 6.5 m/s and 10 m/s (e.g. in the south of Chile) [9]. Generating power from wind hence would not present a cost-effective solution in the site under consideration in this study.

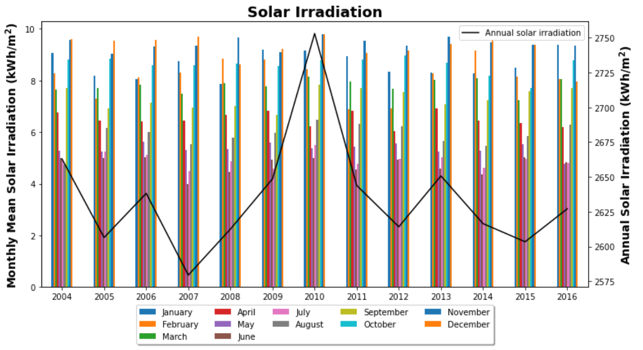

Figure 3. Monthly mean solar irradiation in kWh/m² per year (left axis) and annual global horizontal irradiation (right axis) for "Site A" from 2005 to 2016. Data obtained from "Explorador Solar" platform [8].

E. *Chosen system components and costs*

As discussed, solar power generation is the most suitable type of RE source in the area. When using solar PV, the most mature RE technology today, we need to add another power source for hours during which the PV generation cannot cover the demand, hence forming a HES. Among available alternatives, one can couple the PV park with either diesel generators, as they are already used on site today, or with a battery park. These two scenarios shall be compared to a diesel generators-only scenario, which is today's setup of the current telescopes in the area.

To adequately optimize microgrids for use on the site, cost assumptions need to be made for all three potential components. The cost estimations in this work were made for Chile in 2030, and adjusted to 2020 US-Dollars (real2020).

Costs for system components vary widely today. In 2020, the capital expenditures (CAPEX) for one kW peak (kWp) of PV arrays had a median of 748 $/kWp, ranging between 705-999 $/kWp in Chile [10]. Laying the cost decrease assumptions from [11] on 2020's median array costs results in a price decline as shown in Fig. 4. The error margins for the sensitivity analysis display IRENA's most conservative and most progressive cost decline assumptions [12]. For batteries, we follow NREL's latest cost decline assumptions down to 280 $/kWh in 2030 [13], adding a sensitivity window of ± 20% (also Fig. 4). Diesel generator CAPEX and diesel prices are assumed to remain constant from between 2020 and 2030. Table I gives an overview of all costs included in the optimizations, including operation expenditures (OPEX).

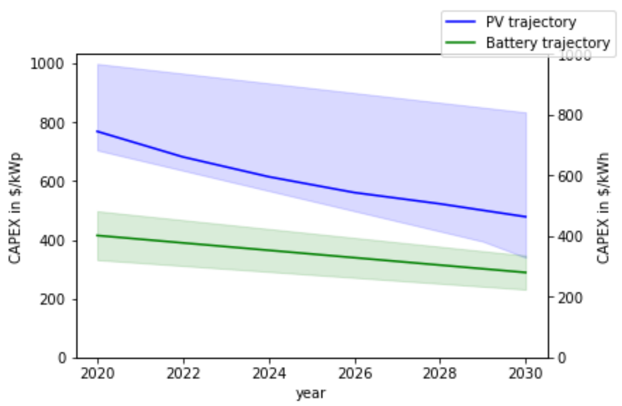

Figure 4. Cost trajectory for PV park (left axis), 1 MW battery park (right axis) from 2020 to 2030.

TABLE I. SYSTEM COMPONENT COSTS FOR 2030

Type of cost	Value	Unit	Source
PV CAPEX	478.5	$/kWp	[10], [11]
PV OPEX	2% of CAPEX	$/kW	[15]
LFP battery CAPEX	280	$/kWh	[13]
LFP battery CAPEX	2797	$/kW	[13]
LFP battery fixed OPEX	8.16	$/kW/yr	[13]
LFP battery variable OPEX	0.5125	$/MWh	[13]
Diesel generator CAPEX	448	$/kW	[15]
Diesel generator fixed OPEX	2% of CAPEX	$/kW	[15]
Diesel generator variable OPEX	10	$/MWh	[15]
Diesel price	1.0024	$/L	10-year average 2011-'21 [16]

Two different power system environments were used in this work: HOMER Pro and the highRES model written in GAMS.

F. *Optimization with HOMER*

HOMER Pro is an economic optimization software for microgrids [14], which optimizes systems to lowest net present costs, i.a. the present value of all the costs the system aggregates over its lifetime.

For each of the three scenarios, it found the economically optimal setup of installed capacities to cover the demand of AtLAST and San Pedro de Atacama. This required a number of economic parameters. The data and assumptions included in the optimization were:

- The load of both AtLAST and the city need to be covered; installation diesel generators in scenarios 1 and 3 is allowed in increments of 100 kW;
- Minimum load ratio of diesel generators is 25%;
- The GHI profile from subsection 2G is used as the irradiation input;
- The PV park and batteries for scenarios 1 and 2 are scaled by the HOMER optimizer;
- The system is set to have a lifetime of 25 years, where PV arrays and diesel generators have a lifetime of 25, batteries of 15 years;
- PV arrays are subject to a derating factor of 80%;
- The battery park's CAPEX are only based on $/kWh, as $/kW could not be inputted;
- Fixed OPEX were priced into the CAPEX of the components;
- Transmission lines were not considered.

G. *Optimization with GAMS*

To model and simulate the proposed HES through GAMS, we adapted the optimization model proposed by Price and Zeyringer [17] for the energy system of Great Britain and Europe [18]. This model was constructed to design a cost-effective power system, based on the minimization of capital and operational costs and to meet hourly demands and technical constraints. The main outputs of this model are the dispatch and locations of power plants as well as the investment and location of RE technologies and storage systems.

For the present case, the model was modified to optimize the dispatch of power plants and the investment of RE technologies. The location of each technology (diesel generator, PV park, and battery storage system) was considered fixed (see subsection 2C). Moreover, we assumed that the transmission grid between each point exists and the connections are straight lines as is shown in Fig 3.

Tab. II shows a summary of the technical information used for the model. It should be noted that in the present model, to calculate the CAPEX of the storage system, both the capital costs for the storage power ($/kW) and for the storage capacity are considered ($/kWh) (see Tab. I).

TABLE II. TECHNICAL INFORMATION USED FOR THE OPTIMIZATION MODEL IN GAMS

Parameter	Storage system	Generation technologies
	LFP Battery (1 MW)	*Diesel generator*
Round-trip efficiency (%)	90	
Power to energy ratio (hr)	4	-
Availability factor (%)	95	95

III. RESULTS

A. Scenario results in HOMER

In the optimization with HOMER, the lowest net present cost system for each of the three scenarios given was calculated. Additionally, the micro grid setup with the overall lowest net present costs was found, which could include any of the three generation options. Fig. 5 shows the resulting installed capacities, annual power production by generator, percentage of RE curtailed annually and the yearly carbon footprint for the three scenarios and the cost-optimal solution of the system as an additional case.

Looking at annual carbon emissions, all HESs, i.e. setups that allow building PV capacities, have a significantly lower carbon footprint than the system that consists only of diesel generators. The system consisting of PV and batteries (scenario 2) has – as can be expected – no direct GHG emissions. However, also a setup with PV and diesel generators (scenario 1) can lower the carbon footprint by 38%, whereas the micro grid with the lowest net present costs (Cheapest case) would also avoid 95% of the emissions of scenario 3, Just Diesel.

The PV capacities in the different scenarios vary widely and are clearly oversized in all cases that contain PV arrays in comparison to the peak demand of 3.4 MW. This results in curtailment of produced power between 54 and 80%.

The net present costs of the different scenarios are depicted in Fig. 6. The variations from 33.6M $ to 80.2M $

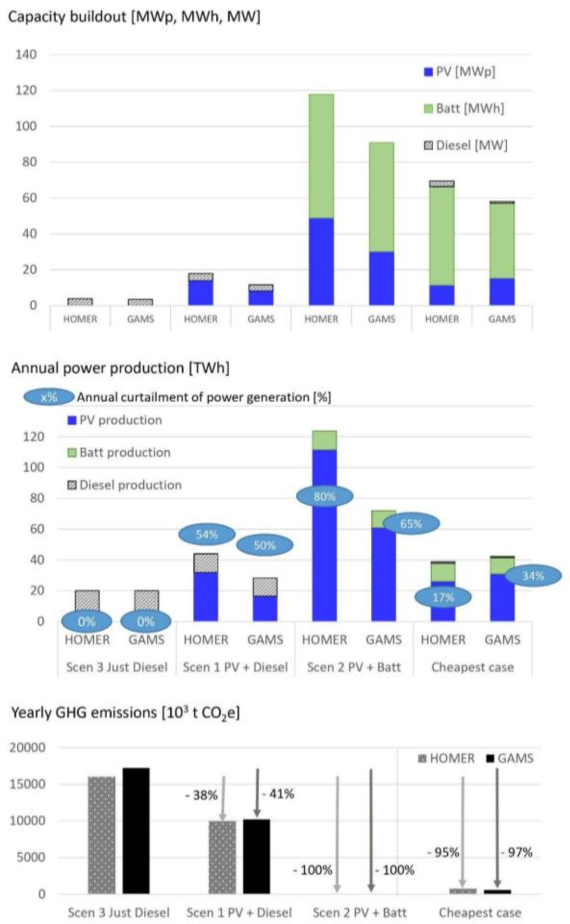

Figure 5. Installed capacities, annual power production and GHG emissions for optimization cases in HOMER and GAMS.

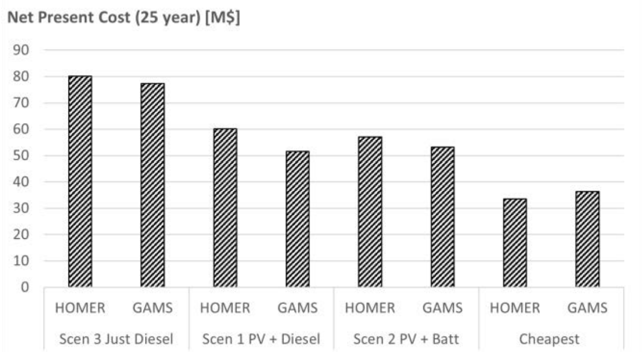

Figure 6. Net present costs for optimization cases in HOMER and GAMS.

make it clear that the choice in technology has a strong impact on the cost that the new telescope has to pay for its power supply. Scenario 3, Just Diesel, stands at the top due to its fuel costs, which in the long run clearly offset the advantage of the lower CAPEX of diesel generators.

A closer look at the Cheapest case scenario reveals that the diesel capacities built are mainly used during some days with little solar energy in June, see Fig. 7.

To find out how large of an influence the cost assumptions have on the optimization cases, in the next step a sensitivity analysis was performed.

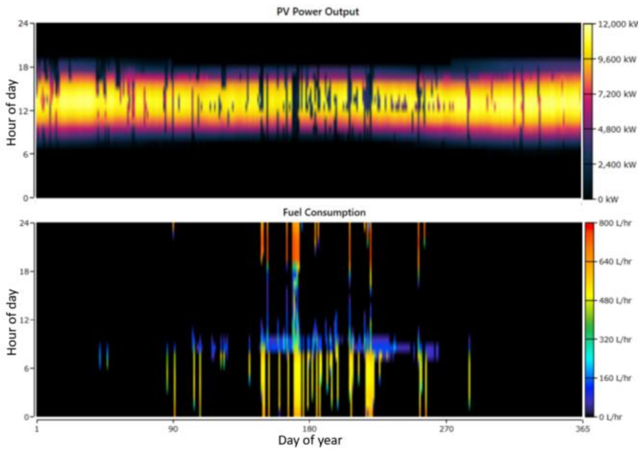

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Figure 7. PV power output compared to diesel fuel consumption over the simulated year.

B. *Sensitivity analysis in HOMER*

To test how sensitive the HOMER optimizer would react to changes in the input values, we performed a sensitivity analysis by adjusting three cost variables and running the optimizer in the Cheapest case setup. The PV and battery CAPEX were modified according to the more conservative and more progressive cost trajectories described in Fig. 4, whereas the price of diesel in \$/L was spiked up to double the originally assumed value.

Fig. 8 shows that the highest effect on system costs occurs when varying the CAPEX of batteries. In the original cheapest case, batteries made up 68.1% of the initial CAPEX. Increasing or lowering their costs hence shifted the net system costs up and down accordingly. However, the built battery capacity did not change.

Increasing the PV CAPEX had HOMER install 6.6% fewer PV arrays, and increased the annual diesel power generation by 21.3%. The higher PV array costs lead the optimization to shift towards more fossil generation. Conversely, significantly lower array costs resulted in 5.2% higher PV capacity installations and 12% less diesel power generation.

Changes in diesel prices did not have much of an effect on the system's net present costs, as HOMER's "Cheapest case" uses diesel power only to a small extent to cover demand during the cloudier days in June to August.

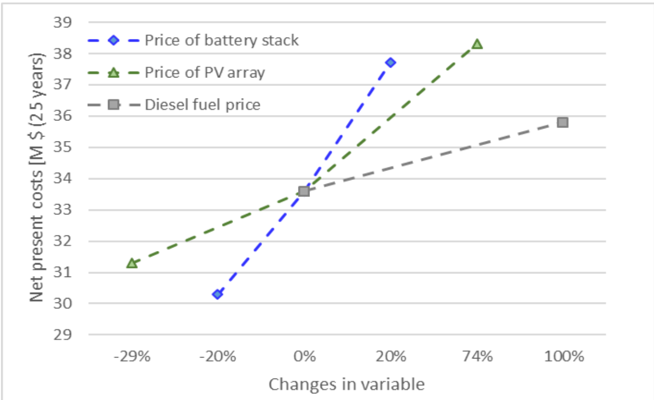

Figure 8. Changes in system net present costs (25 years lifetime) in the cheapest case considering changes in three different parameters for the HOMER results.

C. *Scenario results in GAMS*

Considering the same assumptions and simplifications as in the optimization with HOMER, a HES for AtLAST and the community of San Pedro de Atacama was designed in GAMS. This was achieved by minimizing the total cost of the system (annualized investment and operational costs) for one year (2030), and thus obtaining both the optimal size of each system component and the optimal dispatch of power flows. Fig. 5 shows the resulting installed capacities, the GHG emissions, and the percentage of RE curtailed for the three scenarios and the cost-optimal solution for the system.

From these results, we can see that the installed capacity for the diesel generator in scenarios 1 (PV + Diesel) and 3 (Just Diesel) are the same. In the latter case, however, the power generation is almost 1.6 times higher than in the first case. This difference is due to the fact that in scenario 3 diesel generators are the only generation technology, whereas in scenario 1 PV power is used additionally. Furthermore, in terms of the installed capacity of PV, scenario 2 (PV + Batt) presents the highest value because this generation technology serves two goals: to meet the electricity demand and to charge the storage system for overnight use.

Considering the percentage of curtailed energy in the two scenarios that include PV (scenarios 1 and 2), the scenario using PV + Diesel presents the lower value with 50%. In this scenario, the PV arrays produce 1.5 times more energy than the diesel generators. Thus, the resulting PV system is oversized and only half of the electricity generated is used for the demand. Scenario 2 (PV + Batt) entails even more curtailment, since its PV capacity exceeds that of scenario 3 by a factor of 3.

Comparing the climate impact of the three main cases (without considering the cost-optimal case), scenario 2 obtains the lowest direct GHG emission (the emissions due to manufacturing/installation being not considered). Conversely, the worst case in terms of climate impact is scenario 3 as in this, the only generation runs on fossil fuel.

Comparing the net present costs (see Fig. 6), scenarios 1 and 2 are the cheaper options among the three scenarios (without considering the cost-optimal case), with scenario 1 undercutting the other one by only 2%. These results are consistent with the reported cost in Tab. I, where PV and diesel generation are the cheapest investment options, and the PV and battery storage system have the lowest variable OPEX costs.

Observing the cost-optimal solution (Cheapest scenario), we can see that the best alternative in terms of net present costs is to install and use a combination of the three alternatives considered: the PV arrays to cover the demand during the day, the battery storage system during the night, and the diesel generation for some days during autumn and winter. Observing the GHG emissions of this solution, it presents a reduction of 97% in comparison to using only a diesel generator (current situation of San Pedro de Atacama and the telescopes ALMA and APEX). This represents a significant improvement in terms of GHG emissions, but scenario 2 would be even more climate friendly. However, the scenario with PV and batteries comes with higher net present costs, as a bigger PV and storage system needs to be installed to cover the demand during autumn and winter.

IV. Conclusion and Outlook

The two microgrid optimization approaches used, though based on the same demand estimations and cost assumptions, resulted in slightly different optimal microgrid setups. This is due to the particular setup and assumptions that needed to be taken in the respective approach. In particular, the CAPEX of batteries were only entered as costs per energy, but not costs per power in HOMER, leading to differences in the building of batteries.

The results obtained with both electricity system models point in the same direction. HES would result in lower costs as well as lower emissions compared to using a single generator microgrid. The system with the lowest costs includes both diesel generators and batteries to balance the solar power's intermittency, and would decrease GHG emissions by 95/97% compared to the case using just diesel. Coupling PV arrays with diesel generation alone would decrease GHG emissions by 38/41%, while coupling PV generation and batteries obviously completely eliminates the carbon footprint of the microgrid.

Both approaches had extreme curtailment rates when PV arrays were coupled with only batteries or only diesel generators. While curtailment rates of 20 to 30% can be seen in microgrids today, curtailment rates of 50 to 80% seem impractical. In the case that optimized for lowest system costs, HOMER and GAMS resulted in more robust systems that curtailed only 17-34% of the total power generation. The curtailment issue needs further addressing in future works. Applying curtailment restrictions in the optimization can lead to more realistic systems with smaller PV parks. Such restrictions could not easily be put in place in HOMER, but could easily be added through an additional restriction to the GAMS optimization problem.

The lifetime of the system components was taken from HOMER's initial settings. Admittedly, batteries with such a high throughput would likely have to be replaced more frequently than every 15 years, which would increase the battery costs in the system and might drive the cheapest case optimization towards a higher diesel usage. This is a sensitivity analysis that should be considered in the future.

Moreover, one should look into combining batteries with seasonal energy storage options such as hydrogen in a hybrid energy storage system. This could store excessive PV energy to cover the demand during lower irradiation times in the Chilean winter and would be a sensible alternative to a battery park as the sole form of energy storage.

Acknowledgement

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