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CONCENTRATING SOLAR POWER (CSP) PLANTS FIT PERFECTLY WITH CHILEAN MINING INDUSTRY. OPTIMAL DESIGN CHALLENGE

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Abstract

Concentrated Solar Power (CSP), in conjunction with Photovoltaic (PV) technology, allows providing clean, economic and reliable power supply to operational mining industry by means of optimal hybrid designs. This allows leveraging photovoltaic's (PV) ultra-low Levelized Cost of Electricity (LCOE) during solar hours with economic and highly flexible CSP technology to cover for intra-day Plane Of Array irradiation (POA) variability, daily ramping of the PV solar field and night hours supply of power. The present work provides a simulation programming based approach to estimate the cost effectiveness of a greenfield co-located hybrid CSP-PV system to supply a real mining operation electric demand profile using real meteorological data and up to date national cost structures.

Keywords: CSP, PV, hybrid solar plant, mining, optimization, mathematical programming, simulation, sequential linear programming, sustainable mining

1. Introduction

Chile is a world class mining country, defining a portion of about two thirds of its GDP, and electric consumption, by mineral extraction and processing endeavors (copper, molibdenum, gold, silver, etc.). But the long country is also a world-class destination for developing renewable projects such as PV and CSP, due to its well-endowed geographical situation (the Andes mountain chain on the east blocking humidity especially in the North) and maritime conditions (Humboldt Current with cold water on the west); it allows finding high irradiation zones throughout the complete territory. The most preferred locations are the northern part, for both CSP and PV (identifying measured values of up to 3 800 and 2 600 of DNI and GHI respectively, both in kWh/m^2/year) and the central-southern part for PV (this zone presents lower values but still considered world-class irradiation). Given the coincidence that a large portion of the mining processes take place in the northern part of Chile, the opportunity arises for developing a supply-demand ecosystems, which is economical, sustainable and reliable using solar energy and storage technologies. This also goes in line with the current trends of more products going green and end users are requesting green products. E.g., Codelco, one of the big copper mining industries in Chile, was asked by BMW (German automobile provider) to produce green copper for their cars. This trend is important for the Chilean mining industry, where a big amount of emissions arise by energy consumption of the mining industry.

This work addresses the issue of supplying 100 % of the electricity demand of real mining operations using real granular profiles of demand and supply (both co-measured DNI and GHI) calculating economic indices such as LCOE, overnight investment costs, operational costs, water and CO_2 direct foot print, among others.

2. Context

The worldwide power systems, and more generally the energy sector as a whole, face the challenge of decarbonization by either implementation of new and emerging low carbon technologies, regulatory changes (such as new market designs) or new policies (CO_2 taxes, Feed in Tariffs, Renewable Portfolio Standards, etc.). Under the realm of new and emerging technologies PV and wind have taken the economical lead primarily thanks to policies followed by market forces and to considerably decrease in specific capital

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expenditure (CAPEX), technological improvements (materials, simulation, management, etc.) and a better understanding in overall power systems on how to integrate variable and uncertain generation in the daily operation of an electricity market. Although solar PV and wind technologies are cheap to build and operate (in LCOE) terms, both of these technologies are inherently not available at all hours (variable) and present some level of uncertainty in their availability and ramps on different time scales. These aspects (variability and uncertainty) present challenges of sufficient and reliable supply of electricity on either islanded-isolated systems or medium to large-scale grid-connected power systems. Present understanding of the expected evolution of power systems indicates the need for integration of conventional flexible units like natural gas fired turbines or combined cycles, energy storage, increased transmission capacity for regional integration and demand response. This always taking into account the specific parameters of electric demand and supply that each region has, such as vegetative (residential) and industrial demands and primary energetic availability (hydro inflows, solar irradiance, wind speed profiles, etc.). By understanding the need for storage, flexible and economical solutions that take into account the specific supply conditions (availability of resources) and the demand (already existing ecosystem of foreseeable demand), this work addresses the issue of optimally designing and sizing of a fully solar supply of electricity to an operating mining industry considering PV, CSP coupled with molten salt thermal storage and battery energy storage systems (BESS) as technology options.

Section 3 presents the conceptual problem, which need to be solved and the current state of the art, how to tackle the problem; Section 4 contains the proposed methodology, how the problem is addressed; Section 5 presents the study case parameters; Section 6 presents the study case results, and Section 7 presents the conclusions, discussion and next steps.

3. Conceptual problem

The state of the art of optimal design of hybrid CSP+PV plants illustrates several methodologies to perform such a task. Virtually all of the reviewed works used a thermo-dynamical simulation environment [15, 3, 11, 18, 7, 16, 17], together with pre-defined dispatch (p premises and policies to operate the hybrid plant. To a lesser extent other works used hourly profiles of energy spot market prices, which in conjunction with dispatch optimization heuristics, aimed at maximizing expected profits. Both approaches rely on parameterization (discretization) of the solution space (design variables), which is computer intensive but tractable using parallel threads, reasonable simulation time steps and a finite set of steps of discretization of the design hyper space. Only one work [14] utilizes direct Mixed Integer Linear Programming (MILP), in contrast to solution space sampling, to optimize the aforementioned design variables. Secondly, none of the reviewed works addresses the problem considering an explicit market simulation (and thus endogenous dispatch policies and energy spot market prices) for performing the optimization. The latter point could be important, considering that dispatch policies on liberalized markets are mainly dictated by market dynamics. The general thought is that optimizing a hybrid plant in conjunction with long-term market uncertainty (stochastic) could yield in lower risk designs for investors.

In this sense, the literature identifies works on optimizing the operation on day-ahead and real-time markets [20], which is one step away from the previous elevated problem of designing an optimal hybrid plant with a lower level problem of market operation and uncertainty.

Considering that MILP formulations for the design of hybrid solar plants are not mature and well-approved, in conjunction with the lack of co-optimization of the design together with market equilibriums, this work investigates on both points by firstly optimizing a hybrid plant for supplying an islanded mining operation using a sequential linear programming SLP approach and secondly optimizing the supply of electricity of a mining operation with the opportunity to sell the excess power at a given price, again using SLP. The latter task does not fully incorporate the uncharted territory of designing hybrid solar plants through mathematical programming with equilibrium constraints (MPEC), but it is intended to do so in the future.

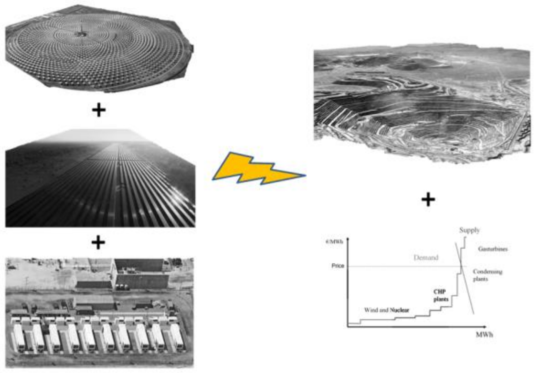

Figure 1: Supply-demand problem scheme.

Specifically for this work, it was looked for a deterministic demand that fits perfectly with the solar energy coming from CSP, PV and BESS technologies (see Figure 1), specifically choosing solar field size (capacity), storage capacity (thermal and electro-chemical). The specific design variables for the simulation are given in Table 1.

Table 1: Design variables.

Plant	Design variable	Unit
Central receiver CSP plant	Power Block	kWac
	Heliostat field	m^2
	Tower	m
	Receiver	kWt
	Storage	kWht
PV	PV field	kWdc
	Tracking/Fixed structure	m^2
	Inverter	kWac
BESS	Energy	kWhac
	Capacity	kWac

4. Methodology

This chapter details the mathematical formulation of the problem, how non-linear features of the design problem are incorporated, which assumptions/limitations are made and the overall technologies that are considered.

a. Formulation

The proposed linear formulation aims at minimizing the annual cost of electric supply of a mining operation defined by a consumption profile subject to different constraints. The formulation is the following:

$$minimize\ annual\ cost: CSP_{annuity} + PV_{annuity} + BESS_{annuity} + \tau\left[\sum_{t}^{T} \tau\left(CSP_{OP} \cdot g_{csp,t} + VOLL \cdot ue_t\right) - \sum_{t}^{T} SP \cdot spot_t\right] \quad (1)$$

Subject to financial constraints

$$CSP\ annuity: CSP_{annuity} = AFC_{CSP} \cdot IC_{CSP} + (SF_{CSP} \cdot sf_{CSP} + R_{CSP} \cdot r_{CSP} + S_{CSP} \cdot s_{CSP})CRF_{CSP} \quad (2)$$

$$PV\ annuity: PV_{annuity} = AFC_{PV} \cdot sf_{PV} + (SF_{PV} \cdot sf_{PV} + INV_{PV} \cdot ic_{PV})CRF_{PV} \quad (3)$$

$$BESS\ annuity: PV_{annuity} = AFC_{BESS} \cdot ic_{BESS} + (E_{BESS} \cdot e_{BESS} + C_{BESS} \cdot c_{BESS})CRF_{BESS} \quad (4)$$

$$Technology\ a.r.c: CRF_k = \frac{D}{\left[1 - \frac{1}{(1+D)^{T_k}}\right]} \quad (5)$$

Subject to general power balance constraints:

$$Power\ balance: D_t + spot_t + ch_{BESS,t} = g_{CSP,t} + g_{PV,t} + dis_{BESS,t} \cdot \eta_{BESS,dis} + ue_t \quad (6)$$

Subject to specific CSP constraints:

$$Heliostat\ field: DNI_t \cdot sf_{CSP} \cdot \eta_{SF,t} \cdot 10^{-6} = p_{rec,t} + spill_{CSP,t} (7)$$

$$Receiver\ sizing: p_{rec,t} \leq r_{CSP} (8)$$

$$Receiver\ interface: p_{rec,t} \cdot \eta_{R,t} = p_{pbd,t} + ch_{CSP,t} (9)$$

$$Thermal\ storage\ balance: sc_{CSP,t} = sc_{CSP,t-1} \cdot \eta_{TS} + \tau\left[ch_{CSP,t} \cdot \eta_{TS,ch} - dis_{CSP,t}\right] (10)$$

$$Thermal\ storage\ sizing: sc_{CSP,t} \leq s_{CSP} (11)$$

$$Power\ block\ thermal\ balance: p_{pbt,t} = p_{pbd,t} \cdot \eta_{pbd} + dis_{CSP,t} \cdot \eta_{TS,dis} (12)$$

$$Power\ block\ thermo/electric\ balance: p_{pbe,t} = p_{pbt,t} \cdot \eta_{pb} (13)$$

$$Power\ block\ thermal\ limit: p_{pbt,t} \leq P_{PBT} (14)$$

$$Rump\ up\ constraint: p_{pbe,t} - p_{pbe,t-1} \leq RU_{CSP} (15)$$

$$Rump\ down\ constraint: p_{pbe,t-1} - p_{pbe,t} \leq RD_{CSP} (16)$$

Subject specific PV constraints:

$$PV\ field: POA_t \cdot sf_{PV} \cdot \eta_{PV,t} \cdot 10^{-6} = p_{PVDC,t} + spill_{PV,t} (17)$$

$$PV\ inverter: p_{PVDC,t} \cdot \eta_{PV,t} = g_{PV,t} (18)$$

$$PV\ inverter\ sizing: p_{PVDC,t} \leq ic_{PV} (19)$$

Subject to specific BESS constraints:

$$BESS\ energy\ balance: sc_{BESS,t} = sc_{BESS,t} \cdot \eta_{BESS} + \tau\left[ch_{BESS,t} \cdot \eta_{BESS,ch} - dis_{BESS,t}\right] (20)$$

$$BESS\ energy\ sizing: sc_{BESS,t} \leq e_{BESS} (21)$$

$$BESS\ capacity_{ch}\ sizing: ch_{BESS,t} \leq c_{BESS} (22)$$

$$BESS\ capacity_{dis}\ sizing: dis_{BESS,t} \leq c_{BESS} (23)$$

Subject to sufficiency constraint:

$$Sufficiency: {\sum_t^T ue_t}\Big/{\sum_t^T D_t} \leq UE_{max} (24)$$

Subject to market constraint:

$$Spot\ sell: \sum_t^T spot_t \leq SPOT_{max}\ (25)$$

Where sf_{CSP} is the amount if active surface of heliostat field in m^2, r_{CSP} the capacity of the receiver in MW_t, s_{CSP} the thermal storage capacity in MWh_t, sf_{PV} the PV solar field in MW_p, ic_{PV} the PV inverter capacity in MW_p, e_{BESS} the BESS energy capacity in MWh_e, c_{BESS} the BESS converter capacity in MW_e, $g_{k,t}$ power generation of the technology *k* on instant *t* in MW_e, ue_t un served energy on instant *t* in MW_e, $spot_t$ the amount of power sold at the spot market on instant *t* in MW_e, $ch_{BESS,t}$ the charging power of the BESS on instant *t* in MW_e, $dis_{BESS,t}$ the discharging of the BESS on instant *t* in MW_e, $p_{rec,t}$ the power outside the receiver's interface on instant *t* in MW_t, $spill_{CSP,t}$ the lost power of the heliostat field on instant *t* in MW_t, $p_{pbd,t}$ power directly sent from receiver to the power block on instant *t* in MW_t, $ch_{CSP,t}$ charging power from the receiver to the hot salt tank on instant *t* in MW_t, $sc_{CSP,t}$ state of charge of the thermal storage on instant *t* in MWh_t, $dis_{CSP,t}$ discharge power from the hot salt tank into the power block on instant *t* in MW_t, $p_{pbt,t}$ thermal power directly before the power block on instant *t* in MW_t, $p_{pbe,t}$ CSP's gross electric output on instant *t* in MW_e, $p_{PVDC,t}$ direct current power of the PV field before entering the inverter on instant *t* in MW_p, $spill_{PV,t}$ the spilled power on the PV solar field due to clipping on instant *t* in MW_p, $sc_{BESS,t}$ the BESS state of charge on instant *t* in MWh_e. τ the time-step factor in minutes/hour, $VOLL$ value of lost load

(load shedding) in US/MWh$_e$, SP spot price in US/MWh$_e$, AFC_k annual fixed cost of technology k in US/MW, SF_k solar field cost of technology k, INV_{PV} inverter cost in US/W$_p$, CRF_k capital recovery factor of technology k, D discount rate in %/year, T_k economic evaluation time of technology k in years, D_t mining demand on instant t, DNI_t direct normal irradiation profile on instant t, P_{PBT} upper thermal limit of operation of power block in MW$_t$, RU_{CSP} ramp up(down) of thermal power block in MW$_e$/min, POA_t global horizontal irradiation on instant t, UE_{max} sufficiency metric of quality of electric supply in %/year load shed and $SPOT_{max}$ maximum spot selling power in MW.

b. Non-linear features

Non-linear features of CSP and PV technologies are represented through Gauss-Seidel numerical updates of constant efficiency curves on the different stages of the energy management. For avoiding ill-behaved convergence properties (knife edge behavior) a damp coefficient is added to calculate a convex linear combination of the new efficiency and the previous iteration one.

The general update formulation of any non-linear modeled efficiency is:

$$\eta_{k,i,t} = \alpha \cdot \eta_{k,i,t-1} + (1-\alpha) \cdot \pi_k|_{\overrightarrow{Op}} (26)$$

Where $\eta_{k,t}$ is the efficiency coefficient of element *k*, in iteration I and on instant *t*, updated with the previous iteration coefficient $\eta_{k,i,t-1}$ and linearly combined with the new efficiency coefficient $\pi_k|_{\overrightarrow{Op}}$ (calculated from the adjusted curves) and the dampening coefficient α for element *k*.

The considered non-linear features are:

- CSP's receiver loading-efficiency curve: Efficiency polynomial curves adjusted from output results from SAM [21] are used to update the efficiency of the receiver at the operational point.
- PV inverter loading efficiency curve: Efficiency polynomial fractions are adjusted given the efficiency curve from the inverter selected from the SAM database [21].
- Power block loading efficiency curves: Efficiency curves are drawn from SAM simulations of CSP plants [21].

c. Assumptions

The main assumptions of the present work are:

CSP power block:

- The model assumes a 115 MW$_e$ steam cycle power block as a basis for the supply of electricity to the mining operation.
    - Efficiency of power block does not consider environmental impacts like temperature profiles.
- No explicit technical minimums are modeled (use of binary variables), but a two-part efficiency curve of the power block discouraging the operation under part loading.

CSP heliostat field:

- Minutely optical efficiency defined by SAM simulations at a solar field size of 1 million square meters.

CSP receiver:

- Efficiency only a function of thermal power.

CSP molten salt storage:

- Energetic modeling of storage, no temperatures modeled.

CSP self-consumption:

- Self-consumptions profiles (salt pumping, heliostat movement, cooling towers, etc…) can be modeled as functions of the same operation (see non-linear features), in this work they are out of scope.

BESS:

- BESS technology is AC coupled. It is understood that DC coupling could yield better economic results, but is out of scope.

PV system:

- A tracked system profile is assumed to provide energy. More options (profiles) could be added in the future such as fixed tilt systems optimized for winter

Systemic assumptions:

- No inertia constraints are modeled.
- No outages are modeled (reliability).
- Perfect forecast of primary energetics and demand (deterministic modeling).

Solar resource:

- Co-measured solar resource and environmental variables.

Economic assumptions:

- Value of Lost Load (VOLL) is considered to be 1 000 US/MWh_e.
- Spot market price of sold energy between 0 and 10 US/MWh_e.
- Spot market price of purchased energy 200 US/MWh_e.
- Discount rate of 7%/year nominal.
- Economic lifetime evaluation: CSP 30 years, PV 20 years and BESS 10 years.

Algorithm convergence criterion:

- Algorithm convergence at 1 % tolerance.

d. Technologies

The present work considers the use of central receiver CSP technology with molten salt storage coupled with PV technology and BESS. PV technology could in principle be any type of commercial module existing in the market. The same applies to inverter technology.Study case

The present work's study case takes the hourly demand profiles of CODELCO's Radomiro Tomic division for the year 2016 in the Atacama Desert, together with co-measured DNI, GHI and DHI in the Atacama Desert for the same year measured by Fraunhofer CSET (Center for Solar Energy Technologies)

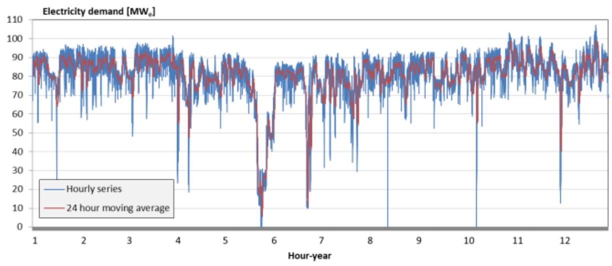

Figure 2: Radomiro Tomic division 2016 hourly demand.

It is evident to see that the size of the mining operation fits the proposed 115 MW_e power block of the CSP plant. For larger mining operations a multi tower system could be optimized.

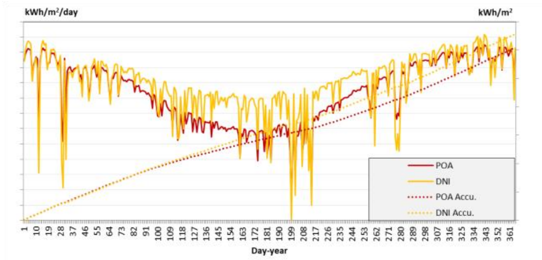

Figure 3: Yearly POA and DNI profiles of irradiation.

The cost structure of the CSP plant to be built is detailed in Figure 4.. This cost structure was developed together with the Chilean Asociation for Concentrated Solar Power as the 2018 vision of CAPEX and OPEX for national (Chilean) energy planning inputs.

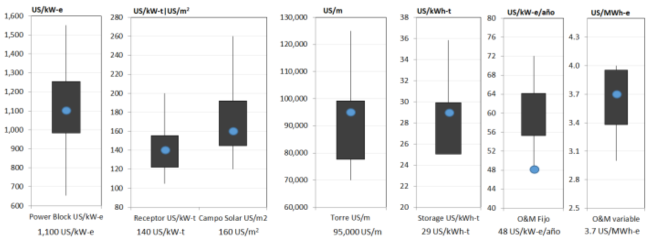

Figure 4: CSP investment and operational economic parameters.

The cost structure for a PV plant considers a specific solar field cost of 0.65 US/W_p, while the inverter value has a specific cost of 0.05 US/W_p. Fix operational costs are 10 US/kW_p/year. The overall CAPEX aims at a value of 0.7 US/W_p and comes from industrial knowledged gathered by Fraunhofer CSET in Chile.

The BESS system considers a specific investment cost of 200 US/kWh_e for the battery system and 100 US/kW_e for the power electronics conversion system.

All the optimization scenarios converge with a predefined tolerance of 1 %. Under the present assumptions (polynomial adjustments of non-linear features) well-behaved properties have been found.

5. Results

The present chapter details the results for the islanded solution and the simple market coupling.

Base scenario simulations are performed using an hourly and 20 minutes interval model for demonstrative purposes of the proposed methodology. Finer time-steps (1 minute without decomposition of the year) can also be applied at the expense of computer processing power and time. Tables illustrate design and operational variables. These are HF (heliostat field), RP (receiver power), S (molten salt storage), SH (hour equivalent storage), SM (solar multiple), SF (PV solar field), IC (inverter based installed capacity), E (BESS energy installed capacity) and C (BESS converter installed capacity).

a. Islanded system

When optimizing for islanded systems the parameter that dominates the technology portfolio of supply is the VOLL, which indicates how costly it would be to shed electric load of mining operations in US/MWh_e and loose productivity. Given that a mining operation is a large supply chain of events and processes is expected to be high. As an example, the Chilean short-term VOLL for the northern region mining sector reaches approximately 1,800 USD/MWh_e for a 24 hour fault [22].

The sufficiency index plays a marginal role, because the cost of not supplying a MWh_e (VOLL) already allows for the annual sufficiency constraint to be met (see Table 3). For the base case solar multiples between 1.6 and 2.0 are identified, together with 12 to almost 19 hours of thermal storage. It is worth mentioning that the PV solar field only grew 5 % from the low to high VOLL scenarios (300 to 1,200 US/MWh_e), while the CSP solar field grew 20 %, this due to CSP’s ability to supply energy round the clock.

The overall yearly mix of supply is 60% CSP and 40% PV, this due to the time availability of GHI for supplying daily demand and CSP for night time demand.

Table 2: Islanded system results for high VOLL values transversal sufficiency values.

Model (minutes per time-step)	Supply quality		CSP					PV			BESS		LCOE
	Sufficiency[1] [%]	VOLL [US/MWh$_e$]	HF [m2]	RP [kW$_t$]	S [MWh$_t$]	SH[2] [h]	SM	SF [MWp]	IC [MWp]	DC/AC ratio [%]	E [kWhe]	C [kWe]	[US/MWh$_e$]
60	3.0%	300.0	869,134	438,698	3,348	12.2	1.6	122.3	86.5	1.41	0.0	0.0	78.0
	30.0%	300.0	869,190	438,726	3,348	12.2	1.6	122.3	86.4	1.41	0.0	0.0	78.0
	3.0%	600.0	974,404	503,609	4,056	14.8	1.8	122.0	86.4	1.41	0.0	0.0	84.1
	30.0%	600.0	974,404	503,609	4,056	14.8	1.8	122.0	86.4	1.41	0.0	0.0	84.1
	3.0%	900.0	1,037,048	538,295	4,774	17.4	2.0	127.7	87.0	1.47	0.0	0.0	87.9
	30.0%	900.0	1,037,049	538,295	4,774	17.4	2.0	127.7	87.0	1.47	0.0	0.0	87.9
	3.0%	1,200.0	1,044,638	542,235	5,057	18.5	2.0	128.0	87.1	1.47	0.0	0.0	90.9
	30.0%	1,200.0	1,044,629	542,230	5,057	18.5	2.0	128.0	87.1	1.47	0.0	0.0	90.9
20	3.0%	300.0	863,900.5	440,303.6	3,329.8	12.2	1.6	117.6	84.4	1.39	0.0	0.0	77.8
	30.0%	300.0	864,031.2	440,370.2	3,330.1	12.2	1.6	117.6	84.4	1.39	0.0	0.0	77.8
	3.0%	600.0	962,827.9	500,968.5	4,100.2	15.0	1.8	120.0	86.9	1.38	0.0	0.0	83.7
	30.0%	600.0	962,882.0	500,996.7	4,100.5	15.0	1.8	120.0	86.9	1.38	0.0	0.0	83.7
	3.0%	900.0	1,031,853.3	541,256.7	4,857.0	17.7	2.0	120.4	86.8	1.39	0.0	0.0	87.5
	30.0%	900.0	1,031,853.3	541,256.7	4,857.0	17.7	2.0	120.4	86.8	1.39	0.0	0.0	87.5
	3.0%	1,200.0	1,053,212.7	552,460.7	5,183.4	18.9	2.0	123.7	87.1	1.42	0.0	0.0	90.3
	30.0%	1,200.0	1,053,212.7	552,460.7	5,183.4	18.9	2.0	123.7	87.1	1.42	0.0	0.0	90.3

1) Sufficiency is the % of allowed annual load shed on energy terms.

2) Equivalent hours of electric full load output at 42% rankine cycle efficiency.

Table 3: Islanded system results of annual energy balance by sources.

Model (minutes per time-step)	Sufficiency [%]	VOLL [US/MWh$_e$]	Supply in GWh$_e$/year				% of supply mix			Solar field energy spillage[1] %/year	
			CSP	PV	UE	Demand	CSP	PV	UE	CSP	PV
60	**3.0%**	300	413.3	275.2	17.0	705.4	58.6%	39.0%	**2.4%**	26.9%	11.0%
	30.0%	300	413.3	275.1	17.0	705.4	58.6%	39.0%	**2.4%**	27.8%	11.0%
	3.0%	600	420.1	274.9	10.5	705.4	59.5%	39.0%	**1.5%**	33.5%	10.9%
	30.0%	600	420.1	274.9	10.5	705.4	59.5%	39.0%	**1.5%**	32.8%	10.9%
	3.0%	900	419.0	279.6	6.9	705.4	59.4%	39.6%	**1.0%**	38.3%	13.4%
	30.0%	900	419.0	279.6	6.9	705.4	59.4%	39.6%	**1.0%**	37.7%	13.4%
	3.0%	1,200	419.3	279.8	6.3	705.4	59.4%	39.7%	**0.9%**	37.3%	13.5%
	30.0%	1,200	419.3	279.8	6.3	705.4	59.4%	39.7%	**0.9%**	37.8%	13.5%
20	**3.0%**	300	419.3	268.6	17.5	705.4	59.4%	38.1%	**2.5%**	27.1%	9.5%
	30.0%	300	419.3	268.7	17.5	705.4	59.4%	38.1%	**2.5%**	26.9%	9.5%
	3.0%	600	422.5	272.6	10.3	705.4	59.9%	38.6%	**1.5%**	30.7%	10.0%
	30.0%	600	422.5	272.6	10.3	705.4	59.9%	38.6%	**1.5%**	30.7%	10.0%
	3.0%	900	425.3	273.3	6.9	705.4	60.3%	38.7%	**1.0%**	35.6%	10.3%
	30.0%	900	425.3	273.3	6.9	705.4	60.3%	38.7%	**1.0%**	32.9%	10.3%
	3.0%	1,200	424.0	275.7	5.8	705.4	60.1%	39.1%	**0.8%**	36.3%	11.7%
	30.0%	1,200	424.0	275.7	5.8	705.4	60.1%	39.1%	**0.8%**	38.0%	11.7%

1) Either by defocusing of heliostat field or clipping of inverter.

The optimized operational scheduling uses PV technology during the day and CSP during the night, cloudy days and also for filling the gaps during solar hours (during POA variability). In Figure 5 a high irradiation week allows to see the optimal operational policy of the hybrid plant.

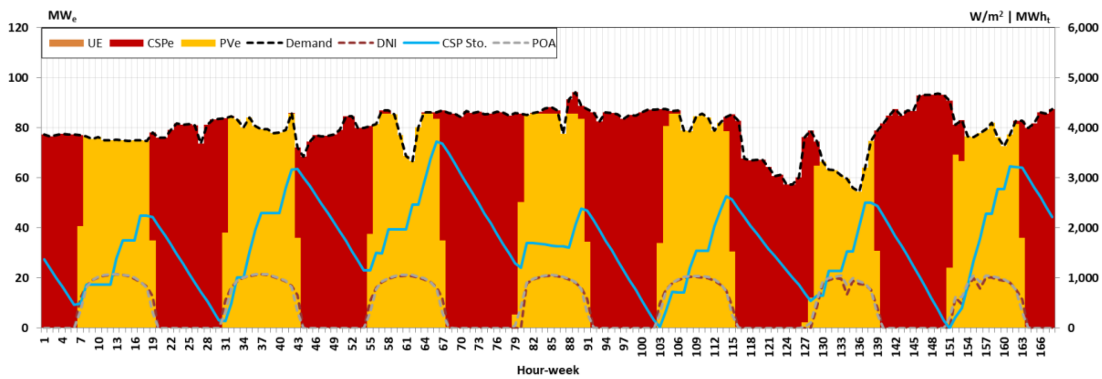

Figure 5: December week with larges DNI available during a three day time period. @VOLL=1.200 US/MWh$_e$ and sufficiency index a 3%. Hourly resolution.

During low irradiation weeks load shedding must be performed loosing productivity at the mines, this shedding event matches a “solar availability collapse” (see Figure 6), which is one of the risks of pushing off-grid operations with high opportunity costs (independent of the technology of energy supply). Grid connected projects offer the benefit of having a large amount of units (large numbers properties in reliability terms).

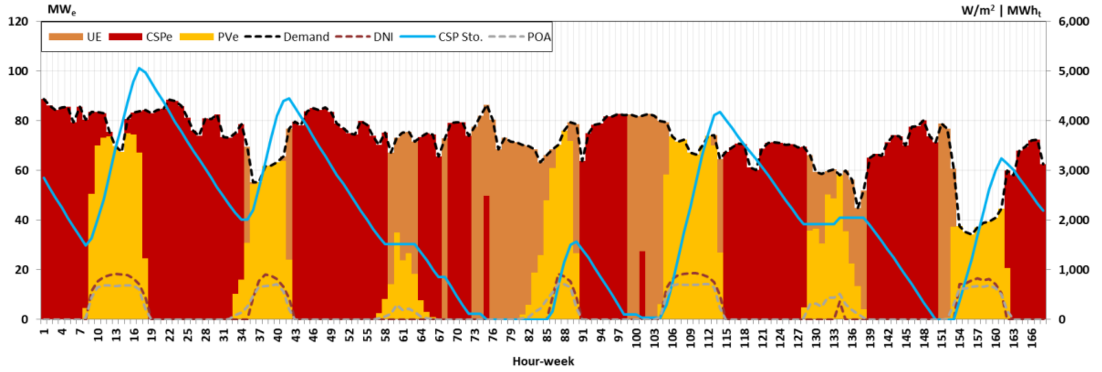

Figure 6: June week with larges DNI available during a three day time period. @VOLL=1.200 US/MWh$_e$ and sufficiency index a 3%. Hourly resolution.

When optimizing with a finer time step (20 minutes, instead of an hour), lower LCOEs are obtained. This could be explained by the availability/demand balance, because we are solving a "similar" problem, but not the same. It could also be the other way around (higher LCOEs). It is unclear if using finer time-steps activates other constraints (such as ramping constraints), changing the vertex of the solution in a large way (see Figure 7 and Figure 8) and increasing the LCOE.

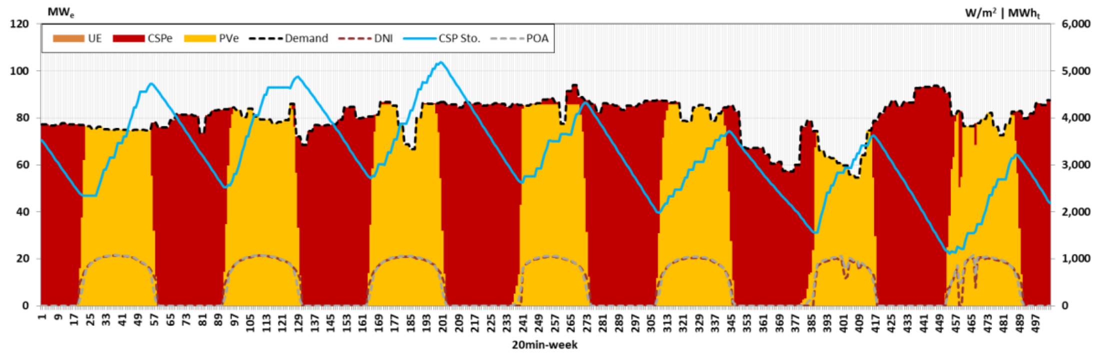

Figure 7: December week with larges DNI available during a three day time period. @VOLL=1.200 US/MWh$_e$ and sufficiency index a 3%. 20 minute resolution.

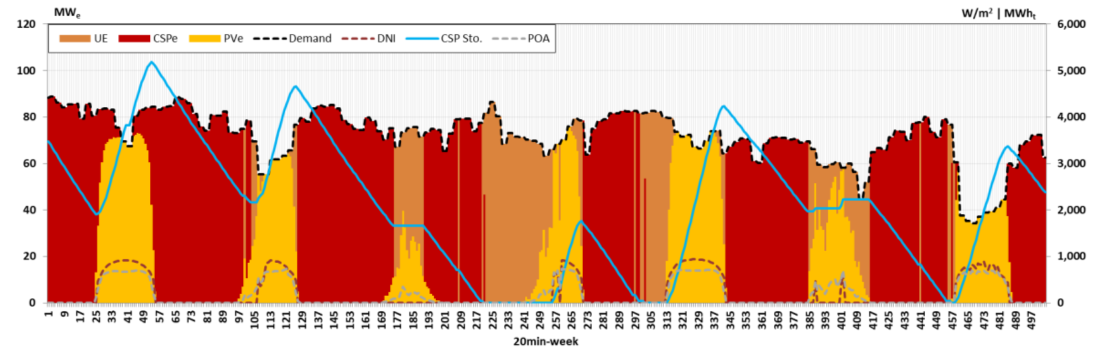

Figure 8: June week with larges DNI available during a three day time period. @VOLL=1.200 US/MWh$_e$ and sufficiency index a 3%. 20 minute resolution.

b. Simple market coupling

As an effort to represent the spot market, this sub-chapter allows to sell excess production power at a conservatively low price (0 to 10 US/MWh$_e$) at the spot market. The results indicate that even small prices such as 5 US/MWh$_e$ allow the LCOE to drastically decrease from 90 to 61.5 US/MWh$_e$ (see Table 4) thanks to the decrease in spillage, less thermal storage and lower DC/AC ratio (see Table 4 and Table 5).

Table 4: Simple market coupling sizing results. @VOLL=1.200 US/MWh$_e$.

Model (minutes per time-step)	Supply quality		CSP					PV			BESS		LCOE
	Sufficiency[1] [%]	Spot market price [US/MWh$_e$]	HF [m2]	RP [kW$_t$]	S [MWh$_t$]	SH[2] [h]	SM	SF [MWp]	IC [MWp]	DC/AC ratio [%]	E [kWhe]	C [kWe]	[US/MWh$_e$]
	3.0%	0.0	1,044,629	542,230	5,057	18.5	2.0	128.0	87.1	1.47	0.0	0.0	90.9
	3.0%	5.0	1,033,032	539,602	4,953	18.1	2.0	136.3	109.0	1.25	0.0	0.0	61.5
	3.0%	10.0	1,081,892	567,935	4,618	16.9	2.1	141.4	116.4	1.22	0.0	0.0	57.4
	15.0%	0.0	1,044,638	542,235	5,057	18.5	2.0	128.0	87.1	1.47	0.0	0.0	89.4
60	15.0%	5.0	1,033,032	539,602	4,953	18.1	2.0	136.3	109.0	1.25	0.0	0.0	61.5
	15.0%	10.0	1,081,892	567,935	4,618	16.9	2.1	141.4	116.4	1.22	0.0	0.0	57.4
	30.0%	0.0	1,044,629	542,230	5,057	18.5	2.0	128.0	87.1	1.47	0.0	0.0	89.0
	30.0%	5.0	1,033,032	539,602	4,953	18.1	2.0	136.3	109.0	1.25	0.0	0.0	61.5
	30.0%	10.0	1,081,892	567,935	4,618	16.9	2.1	141.4	116.4	1.22	0.0	0.0	57.4
	3.0%	0.0	1,053,213	552,461	5,183	18.9	2.0	123.7	87.1	1.42	0.0	0.0	90.3
	3.0%	5.0	1,047,569	550,047	5,176	18.9	2.0	127.4	101.9	1.25	0.0	0.0	61.4
	3.0%	10.0	1,090,831	575,857	4,685	17.1	2.1	138.8	114.4	1.21	0.0	0.0	56.5
	15.0%	0.0	1,053,213	552,461	5,183	18.9	2.0	123.7	87.1	1.42	0.0	0.0	89.1
20	15.0%	5.0	1,047,569	550,047	5,176	18.9	2.0	127.4	101.9	1.25	0.0	0.0	61.4
	15.0%	10.0	1,090,831	575,857	4,685	17.1	2.1	138.8	114.4	1.21	0.0	0.0	56.5
	30.0%	0.0	1,053,213	552,461	5,183	18.9	2.0	123.7	87.1	1.42	0.0	0.0	88.9
	30.0%	5.0	1,047,569	550,047	5,176	18.9	2.0	127.4	101.9	1.25	0.0	0.0	61.4
	30.0%	10.0	1,090,831	575,857	4,685	17.1	2.1	138.8	114.4	1.21	0.0	0.0	56.5

1) Sufficiency is the % of allowed annual load shed on energy terms.

2) Equivalent hours of electric full load output at 42% rankine cycle efficiency.

Yet again, the annual unserved energy was lower than the annual sufficiency constraint, meaning that the VOLL again is high enough to size a sufficient system (see Table 5).

Table 5: Simple market coupling results of annual energy balance by sources. @VOLL=1.200 US/MWh$_e$.

Model (minutes per time-step)	Sufficiency [%]	Spot market preis [US/MWh$_e$]	Supply in GWh$_e$/year				% of supply mix (Demand+Spot)			Solar field energy spillage[1] %/year	
			CSP	PV	UE	Demand	CSP	PV	UE	CSP	PV
	3.0%	**0**	419.3	280.0	6.3	705.4	59.4%	39.7%	0.9%	37.4%	13.4%
	15.0%	**5**	682.3	341.6	6.2	705.4	96.7%	48.4%	0.9%	5.0%	0.9%
	30.0%	**10**	712.7	357.3	6.1	705.4	**101.0%**	50.7%	0.9%	4.9%	0.3%
	3.0%	**0**	419.3	280.0	6.3	705.4	59.4%	39.7%	0.9%	37.4%	13.4%
60	**15.0%**	**5**	682.3	341.6	6.2	705.4	96.7%	48.4%	0.9%	5.0%	0.9%
	30.0%	**10**	712.7	357.3	6.1	705.4	**101.0%**	50.7%	0.9%	4.9%	0.3%
	3.0%	**0**	419.3	280.0	6.3	705.4	59.4%	39.7%	0.9%	37.4%	13.4%
	15.0%	**5**	682.3	341.6	6.2	705.4	96.7%	48.4%	0.9%	5.0%	0.9%
	30.0%	**10**	712.7	357.3	6.1	705.4	**101.0%**	50.7%	0.9%	4.9%	0.3%
	3.0%	**0**	424.0	275.7	5.8	705.4	60.1%	39.1%	0.8%	35.6%	11.7%
	15.0%	**5**	701.4	318.7	5.7	705.4	99.4%	45.2%	0.8%	4.8%	0.9%
	30.0%	**10**	728.5	350.2	5.6	705.4	**103.3%**	49.6%	0.8%	4.7%	0.3%
	3.0%	**0**	424.0	275.7	5.8	705.4	60.1%	39.1%	0.8%	35.6%	11.7%
20	**15.0%**	**5**	701.4	318.7	5.7	705.4	99.4%	45.2%	0.8%	4.8%	0.9%
	30.0%	**10**	728.5	350.2	5.6	705.4	**103.3%**	49.6%	0.8%	4.7%	0.3%
	3.0%	**0**	424.0	275.7	5.8	705.4	60.1%	39.1%	0.8%	35.6%	11.7%
	15.0%	**5**	701.4	318.7	5.7	705.4	99.4%	45.2%	0.8%	4.8%	0.9%
	30.0%	**10**	728.5	350.2	5.6	705.4	**103.3%**	49.6%	0.8%	4.7%	0.3%

1) Either by defocusing of heliostat field or clipping of inverter.

6. Conclusions, discussions and next steps

This work addresses the challenge of full solar and renewable supply of power to mining operations with hybrid solar plants in the Atacama Desert in the north of Chile with real high granularity demand and generation profiles using sequential linear programming.

For fully off-grid supply, the VOLL parameter dictates the sizing of the CSP solar field and its energy availability. It even sizes the system in such a way that annual sufficiency constraints are not binding (limits are met). A large portion of the energy received by both solar fields has to be spilled due to **off-grid operation**. LCOEs ranging from 78 to 91 US/MWh$_e$ can be found for different VOLL values.

For a simple **market coupling exercise** the flexibility to sell excess power to the grid, even at low prices such as 5 US/MWh$_e$, allows to decrease the LCOE to 60 US/MWh$_e$, due to less thermal storage and DC/AC ratio and also less overall solar spillage.

A co-located CSP plant nearby a mining operation's demand opens a door for low Power Purchase Agreement (PPA) prices due to low commercialization risks, which is the case of northern Chile. The present LCOE metrics calculated in the work are energy only (monomic prices), thus in order to compare with energy PPA prices in Chile they have to include capacity payments, decreasing more their values.

This work also highlights the value of high granularity simulations and also opens the discussion to how high it should be, considering that modern markets trader energy on a 5 minute basis on real time markets were prices shoot-up due to flexibility needs (in contrast with day-ahead markets).

It can be also seen that with the proposed BESS cost structure and used granularity, there was no value on installing electrochemical storage capacity. This can contrast with Chilean reality were BESS are installed to avoid spinning reserve requirements to operating machines (conventional and non-conventional). This is due to the fact that a socialized operating reserve scheme takes place, being privately more economical to install a portion of the requested spinning reserve as BESS than leaving idle generating capacity of power plant.

The present optimization exercise lacks inertial and voltage control concepts, technical minimums and real thermodynamic simulations, which are essential when modeling islanded systems, which are sensitive on these dimensions. Also, these results come from a deterministic model, which are only valid when a perfect forecast is present, which is far from reality. Nevertheless, when a market coupling exercise is performed some of them like inertia and voltage control become less relevant.

Since in Chile virtually all mining operations are grid connected this framework presents a new way for sizing hybrid plants under specific economic performance conditions.

The expected improvements of this model consider 1) integration of market equilibrium constraints creating a sequential mathematical program with equilibrium constraints (MPEC), which allows to endogenously determine the market price outcome of selecting a given plant operate in the market, 2) expanding this MPEC model to be stochastic which allows to consider relevant phenomena such as the hydro stochastic process (relevant in for Chile), uncertain fuel prices and potential policy changes on distributed generation (less demand during solar hours), electric mobility (larger demand growth) and decarbonization exercise, and also 3) add risk metrics such as Conditional Value at Risk (CVaR) to incorporate risk aversion of developers and investors.

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