Abos et al. Energy, Sustainability and Society (2017) 7:7
DOI 10.1186/s13705-017-0109-0

Energy, Sustainability and Society

ORIGINAL ARTICLE Open Access

A case study of a procedure to optimize the renewable energy coverage in isolated systems: an astronomical center in the North of Chile

H. Abos[2], M. Ave[1*] and H. Martínez-Ortiz[2]

Abstract

Background: Renewable energy resources show variabilities at different characteristic time scales. For a given resource and demand pro le, there is an absolute maximum achievable coverage (when limiting the fraction of energy lost during production and delivery to a reasonable value). To reach larger coverage factors, two plausible paths can be taken: a mix of resources with different time variabilities and/or an energy storage system. The case treated in this paper is the electricity supply of an Astronomical Center in the North of Chile. The economical feasibility of both possibilities is explored and compared to a grid connected alternative.

Methods: First, data from local weather stations was collected to have a realistic evaluation of the variability of the solar/wind resource at all time scales. Then, we developed a scalable design of a solar/wind plant and a pumped hydro energy storage system. The free parameters of the design are the maximum installed power for each resource and the capacity of the storage system. Finally, the electricity production is calculated to determine the coverage factor and losses for different values of these parameters.

Results: We found that a coverage factor of 64% is economically feasible for systems without storage. The associated total losses are 24%. To reach larger coverage factors is not economically possible and a storage system must be introduced. If this is done, there is a quantum increase of the total cost of about 30%. However, losses are reduced to about 5% and the coverage factor reaches almost 90%. The cost increase is marginally economically feasible, but it has some other advantages: the consumer is independent of the volatility of electricity prices, and is more sustainable.

Keywords: Wind, Concentrated solar power, Photovoltaic, Pump hydro energy storage, Applications

Background

The time variability of renewable energy resources difficults reaching coverage levels larger than 60%. Energy storage systems are a requirement. Periods of zero net production seem unavoidable unless the renewable energy and storage system are largely overdimensioned. Back up systems based on fossil fuels seem to be unavoidable. Both the energy storage and back up system add an extra cost that has to be paid if such high coverage levels are a requirement.

The case treated in this paper is the electricity supply of an Astronomical Center in the North of Chile. The ESO is the European Organization for Astronomical research in the Southern hemisphere. It operates the VLT (very large telescope), located at Cerro Paranal in the Atacama desert, North of Chile. The E-ELT (European extremely large optical/infrared telescope) in Cerro Armazones (20 km away from Cerro Paranal) is in advanced design phase and will be the largest optical telescope in the world. Finally, the CTA collaboration (Cherenkov Telescope Array) has chosen the Armazones-Paranal site for construction of its Southern Observatory.

When the two new observatories enter in operation, the peak power demand of the Armazones-Paranal site is

*Correspondence: ave@ifsc.usp.br
[1]Instituto de Física de São Carlos, Universidade de São Paulo, CP 369, 13560-970 São Carlos, SP, Brasil
Full list of author information is available at the end of the article

estimated to be $\sim$ 8.5 MW and the total annual energy consumption $\sim$70 GWh. Currently, the VLT is generating its own electricity using fossil fuel-based generators.

The two main characteristics of this consumption center are the strong requirements on the stability of the electricity supply, and the relatively large power demanded. Due to these two factors, the use of liquid fossil fuels is economically un-viable. The only two non-renewable solutions plausible are connection to the Chilean national grid or self production of electricity using generators run with natural gas from a nearby pipeline.

The main renewable energy resources available at the site are wind and solar. In this work, we consider a wind-solar PV plant with Pumped Hydro Energy Storage (PHES). We calculate the coverage factor for different values of total Power, Maximum Energy Storage and *wind to solar* fraction to find energy systems that maximize coverage but with costs below the non-renewable energy solutions. Embedded in this procedure is the fact that renewable energy time variability can be diminished by considering a mixture. An important ingredient of this procedure is the relative cost of each technology. Government estimates are taken when possible.

Additionally, a concentrated solar power (CSP) plant with thermal energy storage is analyzed. This technology is considered separately since the storage system cannot be used by the wind farm.

The design of the systems is not detailed but all sources of inefficiencies are taken into account. The wind and solar input data used is from local weather stations, which provides realistic time series that account for all possible sources of the variability of the resources. Overall, the estimates of electricity production and cost are as realistic as possible so they can be used as a guide if such energy systems are eventually implemented. The total cost of each system includes operation and maintenance over the 25 year lifetime of the astronomical center.

The paper is organized as follows: in "Energy demand" section, the energy demand is described; in "Non-renewable energy systems" section, the non-renewable energy systems and their cost are analyzed; in "Renewable energy resources available in the site: solar and wind" section, the solar and wind data used in our calculations is described; in "Renewable energy systems" section, the methodology to calculate the time series of electricity production for the Wind-Solar PV plant with PHES is presented, together with a modular design of each of the subsystems and their cost; in "Results" section, an algorithm to find the optimum system is presented and compared to the non-renewable energy alternatives. The CSP with thermal storage design and cost are presented in the Appendix.

Energy demand

The energy demand of the VLT is known [1]. The power demand changes from day to night but is rather constant along the year (less than 5% variability). The projected E-ELT (CTA) consumption is taken from ESO estimates [2]. All the sub-systems, including lodging, offices and workshops are included. A simplified model is adopted: a constant power with different day/night values. The start/end for day/night will be calculated using the sunrise and sunset, even though the start/end of astronomical observations is typically later/earlier.

Table 1 shows a summary of the site energy demand. Night consumption is smaller than day for the E-ELT and VLT due to the strict thermal control system.

All observatories work in slow tracking mode during the night. In between observational windows, telescopes are re-positioned to track new objects. The instantaneous power required for re-positioning is large compared to the average power: 700, 3200, and 2000 kW for the VLT, CTA, and E-ELT compared to 1000, 2750, and 4250 kW. However, the total energy for repositioning is small (<5%). The extra power for repositioning can be supplied by energy storage systems with extremely fast responses like flywheels, STATCOMs or a battery system.

Non-renewable energy systems

Connection to the Chilean electrical network

The grid connection alternative envisages the connection of the Armazones-Paranal site to the Paposo substation. It requires the construction of a $\sim$60 km 66 kV line, one 220–66 kV transformer (at Paposo) and one 66–23 kV substation (located halfway between Cerro Armazones and Paranal). The projected investment cost or CAPEX is 12.5 MUSD ($\sim$11 M*e*). The OPEX is calculated multiplying the total annual energy consumed (70 GWh) by a nominal price. Two cases are considered: no inter-annual increase and 1% inflation.

The electrical network in Chile consist of four independent networks, the two most important being *Sistema Interconectado Central* (SIC) and *Sistema Interconectado del Norte Grande* (SING). The electricity market is liberalized but there is a distinction between regulated ($P < 2000$ kW) and special clients ($P > 2000$ kW). Special clients can negotiate directly electricity prices with the producers

Table 1 The day/night power demand assumptions made in this work together with the projected annual energy consumption

	P_{day} MW	P_{night} MW	E_{year} GWh
VLT	1.1	0.9	8.8
E-ELT	4.75	3.75	37.2
CTA	2.5	3.0	24
Total	8.35	7.65	70

and/or produce its own energy. Regulated clients are subject to prices fixed twice a year by the government based on the liberalized market prices. Figure 1 shows the time evolution of the mean market price in Chile for the SING/SIC in Chilean Pesos per kWh and *e* per MWh [3]. Prior the 2007 crisis, prices were around 40 *e*/MWh, and during the last 5 years have been stable around 80 *e*/MWh with 15% oscillations. This is the nominal price that will be considered in this work.

Multifuel generators

A 8.5 MW combined cycle gas turbine (CCGT) is considered in this case: it has high efficiencies ∼55% and fast time responses. Since there is already a 2.5 MW generator with these characteristics in the site, it will be only necessary to upgrade it with 6 MW more. We consider an investment cost of 1000 *e*/kW, i.e., a CAPEX of ∼6 M*e*. Natural Gas supplied by Gas Atacama, whose pipeline passes through the middle of the Armazones-Paranal site, can be used to run these generators. The expected connection cost is ∼ 2.5 M*e*: a gas sub-station, a low capacity (7000 m^3 per day) 5-km pipeline and a low capacity tank for regulation. In total, the CAPEX of the back-up system is 8.5 M*e*.

The OPEX is mainly due to the purchase of natural gas. The natural gas prices are high in Chile. The projections from the Chilean government are taken to correct the world market prices to the special case of Chile. The following equation is adopted to estimate the time-dependent price of a kWh generated by CCGT:

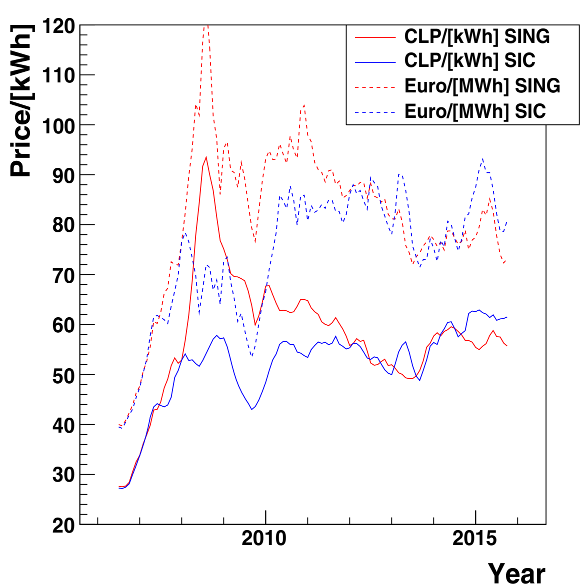

Fig. 1 Time evolution of the mean market electricity price in Chile for the SING/SIC in Chilean Pesos per kWh and *e* per MWh

$$€/[\mathrm{kWh}] = \frac{C_{gas}[€/\mathrm{MMBTU}]}{10^6}\frac{3412\ \mathrm{BTU}}{[\mathrm{kWh}]}\frac{1}{f_{CCGT}} \quad (1)$$

where C_{gas} is given by $(1 + f\ N_{years}) \cdot 9$, N_{years} is the number of years since 2015 and f takes into account the interannual increase of prices. We consider two values: f=0.01 and f=0.1. This equation yields 0.07*e*/kWh for 2015.

Due to the strong requirements on the stability of the supply, this system is also a requirement for all renewable energy systems considered.

Cost estimation

The total cost normalized to year 0 is estimated using:

$$C = CAPEX + \sum_{i=0}^{i=N_{life}} \frac{OPEX_i}{(1+k)^i} \quad (2)$$

where k is the interest rate, 3%. The lifetime of the observatories and the renewable energy system is taken as 25 years. Table 2 shows the results.

Renewable energy resources available in the site: solar and wind

The Armazones-Paranal site is located in the Atacama desert, 130 km south from Antofagasta and 1200 km north of Santiago de Chile. The Cerro Paranal and Cerro Armazones have a height of 2635 and 3000 m respectively, and they are 22 km apart. The Cerro Paranal is 15 km away from the coast.

The topography in the North of Chile is dominated by the Central Andes, characterized by four topographical segments from West to East: the coast mountain range, the central hollow, the pre Cordillera, and the Cordillera. The Armazones-Paranal site is located in the coast mountain range, 20–40 km wide and with mean heights of 1500–2000 m. The coast mountain range falls rapidly into the sea with active segments of sea abrasion where sea cliffs are present and inactive segments where there is an emerged platform.

The climate is typical of a desert region: day/night thermal differences of up to 10 ^oC, rainfall smaller than 30 mm and relative humidities in the 5–20% range. The average temperature is ∼15 with ∼5 ^oC seasonal variations.

Table 2 The total cost after 25 years normalized to year 0 for the non-renewable energy systems

	CAPEX M*e*	OPEX M*e*	Total M*e*
Grid	11	100–112	111–123
CCGT	8.5	84.2–109.5	92.7–120

The solar resource

The solar resource is characterized using the 2011 data from a weather station installed in the area [4]. The measurements available are global and diffuse irradiance in horizontal plane and one axis tracking mode (North-South orientation), temperature. Only 25 days have missing measurements. This data is directly used in the estimation of the electricity production of a solar based renewable energy system. This data contains all sources of time variability and in that sense is more suited for our purpose than satellite based models.

In some special cases, e.g., for missing data periods or to evaluate the inter-annual variability of a wind-solar plant, a simplified model of solar irradiance is used:

$$I_G[W/m^2] = I_D\ (\cos\Phi + f_d) \tag{3}$$

where I_G is the global solar irradiance incident on a surface that subtends an angle Φ with the sun direction, f_d is the fraction of diffuse irradiance and I_D is the direct irradiance in the sun direction:

$$I_D[\ W/m^2] = I_o\ exp(-\tau\ (1 - sec\theta_s)) \tag{4}$$

where θ_s is the solar zenith angle, I_0 the irradiance when the sun is in the zenith and τ is an atmospheric extinction parameter. Adopting f_d=0.05, I_0=1200 W/m^2 [1] and τ=0.1, a good description of the data is found. [2]

Figure 2 shows the global irradiance incident on a horizontal and a one-axis tracking surface from data (dashed lines) compared to the model (solid lines) for the 23rd of June 2011. Figure 3 shows the same for the accumulated day irradiance. 34 days out of the 340 analyzed has a predicted irradiance 10% larger than measured ("Cloudy Days") but only 5 are consecutive.

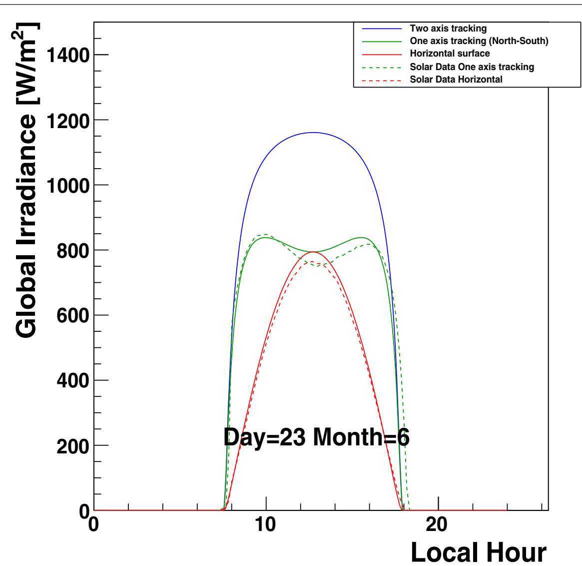

Fig. 2 Global irradiance incident on a horizontal and a one-axis tracking surface from data (*dashed lines*) compared to the model (*solid lines*) for the 23rd of June 2011

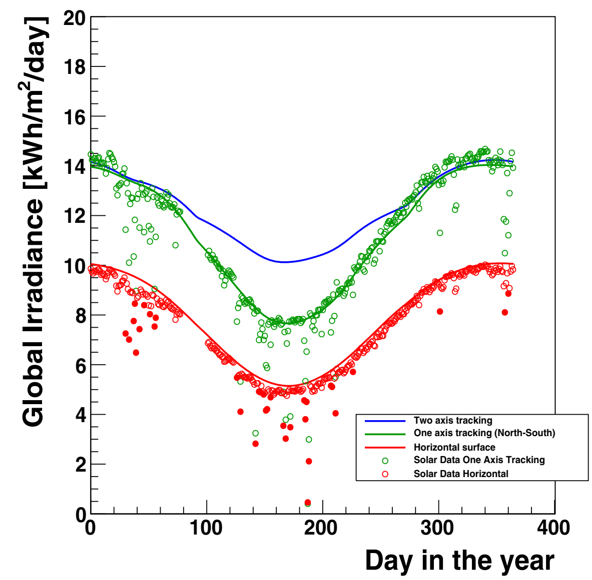

Fig. 3 Same as Fig. 2 but for the accumulated day irradiance

The temperature is also an important factor that determines the performance of solar plants. The weather station temperature time series is used in our calculations.

The wind resource

Wind and speed direction from the VLT meteo mast is used to characterized the wind resource [5]. Measurements at 10 and 30 m from the last 15 years exist. Table 3 shows the average wind speeds at 30 m for the last 10 years. Figure 4 shows the wind speed distribution for the year 2011 at 30 m.

Renewable energy systems

In this section, the methodology to calculate the time series of electricity production for the wind-solar PV plant with PHES is presented. Then, a modular design of each of the subsystems is described. Finally, the procedure to calculate the cost given any value of installed power, wind to solar fraction and size of the storage system is described.

Electricity production time series: methodology

The following definitions will be adopted:

Table 3 Mean wind speed in m/s at 30 m height in Cerro Paranal for the last 10 years

Year	05	06	07	08	09	10	11	12	13	14
$< v >$	6.48	6.46	7.54	6.81	6.19	7.46	7.30	6.84	6.55	7.09

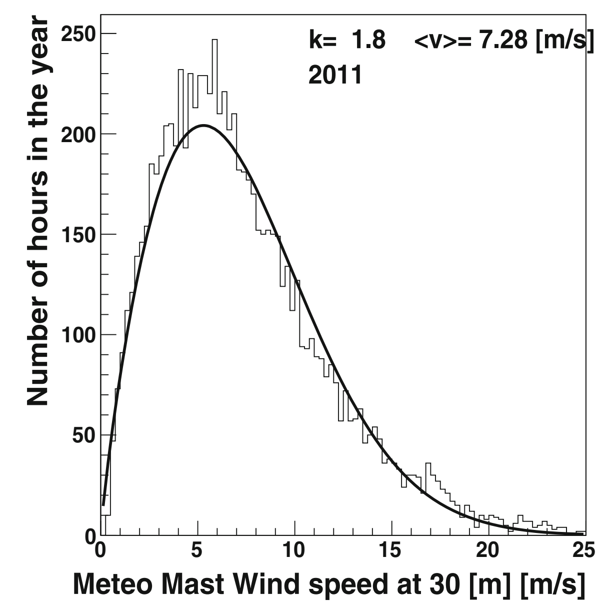

Fig. 4 Wind speed distribution at 30 m in Cerro Paranal for the year 2011

- $P_P(t)$ MW : time series of power produced by solar/wind plant.
- $P_D(t)$ MW : time series of power demand.
- $P_A(t)$ MW : time series of power available to satisfy the demand (either from wind/solar plant or storage system).
- E_S and E_{MSC} MWh: storage level and maximum storage capacity.
- $P^{to\ store}$ and $P^{to\ store}_{max}$: power to store and maximum instantaneous power that the storage system is able to store.
- s_1/s_2 : efficiency of the storage system to store/deliver electricity. It can depend on load.
- $t_1/t_2/t_3$: transport efficiencies (transformer and lines) between solar/wind plant-storage system (t_1), storage system-demand site (t_2) and solar/wind plant-demand site (t_3). $t_1/t_2/t_3$ depends on the location of each subsystem and transmission line type. For our case and using standard calculations they are: 97, 97.5, and 98%.

Time series are calculated in 10 min intervals. If $P_P > P_D$ energy is stored with efficiency $s_1 \times t_1$, unless $P^{to\ store} > P^{to\ store}_{max}$ or the storage system is full. If $P_P < P_D$ energy is extracted from the storage system with efficiency $s_2 \times t_2$ until depleted. The efficiency t_3 is also applied to the fraction of P_P that directly satisfy the demand.

E^{Stg}_{loss} accounts for the energy lost because of $P^{to\ store}_{max}$ and E_{MSC}. E^{Eff}_{loss} accounts for losses due to s_1/s_2. $E^{Transport}_{loss}$ accounts for losses in transport. E^{Avail}_{loss} accounts for availability: it is included assuming that on the 15th day of each month all systems are stopped for maintenance (3.3%). It is only applied to the annual energy production.

E_P,E_D, and E_A are the annual sum P_P,P_D, and P_A. Other definitions:

- $f_{cover}=E_A/E_D$: energy coverage.
- $f^{Stg}_{loss}=E^{Stg}_{loss}/E_P$: energy loss due to storage size and storage maximum power.
- $f^{All}_{loss}=(E^{Stg}_{loss}+E^{Eff}_{loss}+E^{Transport}_{loss}+E^{Avail.}_{loss})/E_P$: total energy loss.

Solar PV plant

We present a modular design of a solar PV plant. The unit cells corresponds to ∼1 MWp. The components of the Solar PV plant selected are the following:

- Solar panels: Jinko Solar JKM300M. This is a silicon poly-crystalline 300 Wp panel. These modules have the IEC61215 certification which is the standard in Europe.
- Inverter/transformer: the Sunny Central SC1000MV. This is a *central* inverter optimal for large system where production is uniform across the array
- Trackers: the ExoSun ExoTrackHZ, suitable for large plants deployed in flat areas. This is a one axis tracker (axis orientation North-South).

The number of panels to be placed in series is calculated using: $N_{series} = V_{op,inv}/V_{mpp,panel}$, where $V_{op,inv}$ is 450–820 V and $V_{mpp,panel}$ is 35–40 V depending on irradiance. This gives between 11 and 23 panels per *string*. The open circuit voltage of a *string* (N_{series}x45 V) should not exceed the maximum operating voltage of the inverter (880 V). For that reason 18 panels per *string* are chosen. 30 *string*s will be connected to a tracker forming a *block*, fulfilling the tracker specifications. All *strings* within a *block* are connected in parallel to an inverter. The number of *blocks* to be connected in parallel to reach the nominal inverter power is given by $\frac{P_{inverter}}{N_{blocks}\times 30\times 18\times P_{nom,panel}}$. This yields six blocks per inverter, which also complies with the restriction that the short circuit current does not exceed the maximum allowable current of the inverter.

Each *string* is a 2 *x* 18 m rectangle. 30 of them are placed consecutively (with a spacing of 7 m) to form a block. The spacing is chosen to minimize shading losses. 3 *x* 3 blocks are placed side by side to minimize DC cabling forming a unit cell, a rectangle of ∼280 *x* 64 m.

The power produced by the solar PV plant in a given time period is given by:

$$P_P[MW] = I_G(\Phi)\,\frac{P_{PV}\,\left[MW_p\right]}{I_{stc}}\,f_{therm.}f_{shading}f_{cte} \quad (5)$$

where $I_G(\Phi)$ is the global solar irradiance on a surface with an incidence angle Φ, I_{stc} the irradiance in standard conditions 1000 W/m^2, the factors $f_{therm.}$ and $f_{shading}$ take into account the thermal and shading losses that depend on irradiance, ambient temperature and sun position, the factor f_{cte} are losses that have no dependencies on the time period considered. The angle Φ is calculated for each period so the solar vector lies within the plane perpendicular to the aperture. The only exception is when the required solar panel elevation is smaller than what trackers allow (40^o, since trackers can rotate $\pm 50^o$). In that case, the incidence angle is calculated for a fixed elevation of 40^o.

The thermal losses are calculated using:

$$f_{thermal\ loss} = 1 - g\ (T_{panel} - T_{std}) \tag{6}$$

where g is the thermal losses coefficient (0.4% per ^oC), T_{std} is the temperature in standard conditions (25 ^oC) and T_{panel} is the panel temperature that can be calculated using:

$$T_{panel} = \frac{I_G(\Phi)}{800}\ (T_c - 20) + T_{ambient} \tag{7}$$

where T_c is the characteristic temperature of the panel, 45^oC in our case, and $T_{ambient}$ is the ambient temperature taken from the weather station.

The shading losses are estimated by geometric calculations for each time period considered. The constant losses are 7%, see Table 4.

Panel degradation is 20% over 25 years. Only the production of the first year is calculated. To maintain it over 25 years, extra power will be deployed that will be accounted in the OPEX of the plant.

Wind farm

Using the meteo-mast data and a topographic map of the area, we followed the standard procedure to design a wind farm. The software WASP is used to generate a wind resource map (WRG), see Fig. 5. Then, the OpenWind Software is used to design wind farms with two, five, and ten turbines. The location is 15 km to the west of Cerro Paranal in the Coastal Cliff, where the wind power density is the highest. The wind turbine chosen is the Alstom ECO 80 2.0 Class 2. It is a pitch regulated 2 MW wind turbine, with a hub height of 80 m, a *cut-in wind* of 4 m/s and a *cut-off wind* of 25 m/s.

The mentioned software does not provide a time series of the produced electricity. This is a problem for our study: an storage system cannot be dimensioned without them. To overcome this problem, we use the following assumption to characterized the time series:

$$\mathrm{P}_P[\,\mathrm{MW}] = \mathrm{N}_{Turbines}\mathrm{P}_{Turbine}(v_{hub}(t), \rho_{air}) \tag{8}$$

where $\mathrm{P}_{Turbine}$ is the turbine power as a function of air density and wind speed at hub height:

$$v_{hub}(t) = v_{30}(t)\, f_{\mathrm{vertical}}\, f_{\mathrm{horizontal}} \tag{9}$$

where $v_{30}(t)$ is the measured temporal series of the meteo mast at 30 m, f_{vertical} is a factor to extrapolate measurements to different heights:

$$f_{\mathrm{vertical}} = U(z)/U(z_{ref}) = (z/z_{ref})^{\alpha},\ \text{with}\ \alpha = 0.05^3 \tag{10}$$

and $f_{\mathrm{horizontal}}$ is a factor that takes into account the geographical variations of the wind speed. The value of $f_{\mathrm{horizontal}}$ is adjusted so Eq. 8 gives the same duty factor as OpenWind.

PHES

The PV and Wind plant requires an electricity based storage system that fulfills the following criteria:

- Power: $\sim$ 10 MW.
- Discharge time at output power: more than 12 h.
- Response time: $\sim$ 10–30 min.
- Lifetime 25 years.
- Efficiency: high, at least 75%.
- Technologically mature.

The only technology that matches these criteria is the pumped hydro energy storage (PHES). The site is located in the Atacama desert where water is scarce. Due to the proximity to the coast, there is the possibility to use sea water as storage medium. However, due to the size of the facility and plausible technological and environmental problems, it is advised the use of desalinated water either self produced or bought.

The PHES plant consist in an upper and lower water reservoir connected by penstocks, and a system of turbines and pumps than convert gravitational energy into electricity or vice versa. The system is closed, so filling of the reservoirs has to be done only once. A separate turbine and pumping system is planned, so typical elapsed times to go from pumping to full load generation are of

Table 4 PV constant production losses

Total	7%
Dirtying	1%
DC cabling	1.5%
AC cabling	0.5%
Inverter	3%
Other	1%

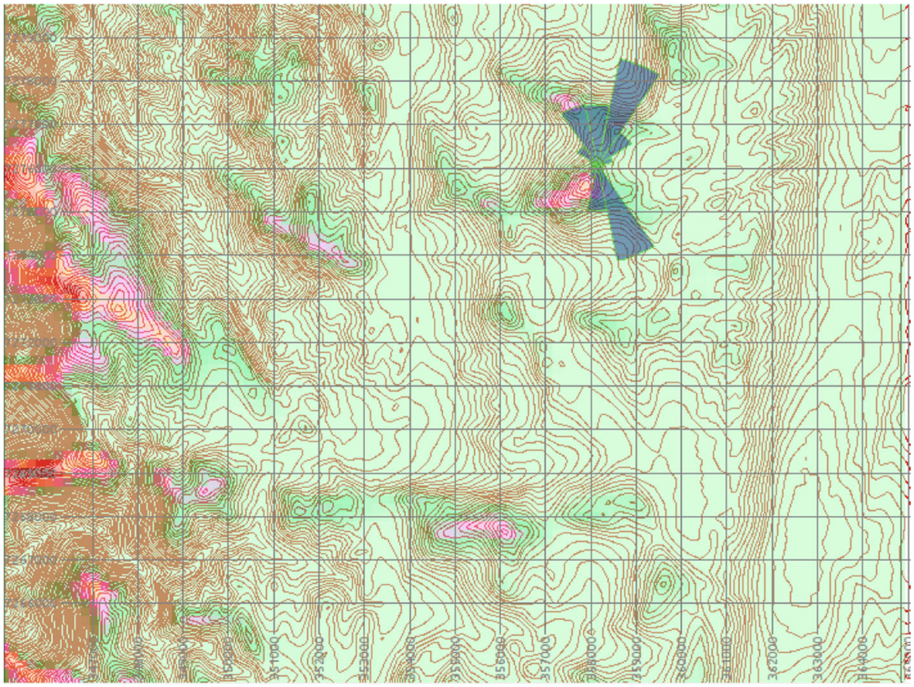

Fig. 5 Map of the wind power density to the west of Cerro Paranal. The wind power density is higher in the *pink areas*. We also show the wind direction rose at the location of the Cerro Paranal. The areas with high wind density on the *left* correspond to the Coastal Cliff, about 15 km away from the Cerro Paranal

the order of minutes. Water evaporation [4] and filtration of water are important and will be taken into account in the design. $P_{max}^{to\ store}$ is fixed to 14 MW, so hydraulic losses does not severely affect the design.

The hydro power in W is given by:

$$P_h = \rho\, g\, \delta h_n\, Q \tag{11}$$

where ρ is the water density in kg/m^3, g is the gravity acceleration constant in m/s^2, Q is the water flow rate through the penstocks in m^3/s, and δh_n is the net height difference given by:

$$\delta h_n = \delta h_g - \delta h(Q) \tag{12}$$

where δh_g is the gross height difference and $\delta h(Q)$ are the hydraulic losses in the whole system that depend on the flow rate. The electric power in generation mode is given by:

$$P_{e\ turb} = P_h\, \eta_{turb}(Q)\, \eta_{gen} \tag{13}$$

where η_{turb} and η_{gen} is the efficiency of the turbine (that depends on load) and the generator. The electric power in storage mode is given by:

$$P_{e\ pump} = \frac{P_h}{\eta_{pump}(Q)\, \eta_{mot}} \tag{14}$$

where η_{pump} and η_{mot} is the efficiency of the pump system (that depends on load) and the motor.

The required value of $P_{e\ turb}/P_{e\ pump}$ is 8.5/14 MW.

The design of the system proceeds in two phases:

- Site selection.
- Plant design.

The site selection implies indirectly choosing two important variables: δh_g and penstock length. The second variable is crucial when determining the hydraulic losses, and is an important contributor to the total cost of the system. As a general rule, larger values of δh_g and smaller penstock length yield smaller investment costs. However, other factors have been analyzed:

- Existence of infrastructures like roads and transmission lines.
- Existence of hydro resources or possibilities to obtain them.
- Earthquake risks.
- Detritus removal: short but intense rainfalls can generate detritus removal that can affect the integrity of the PHES.

Topographic maps have been used to choose four possible sites. All sites have similar availability of water/infrastructures and geological risks. Therefore, the site with larger height difference and the smaller penstock length was chosen. Figure 6 shows a detailed topographic

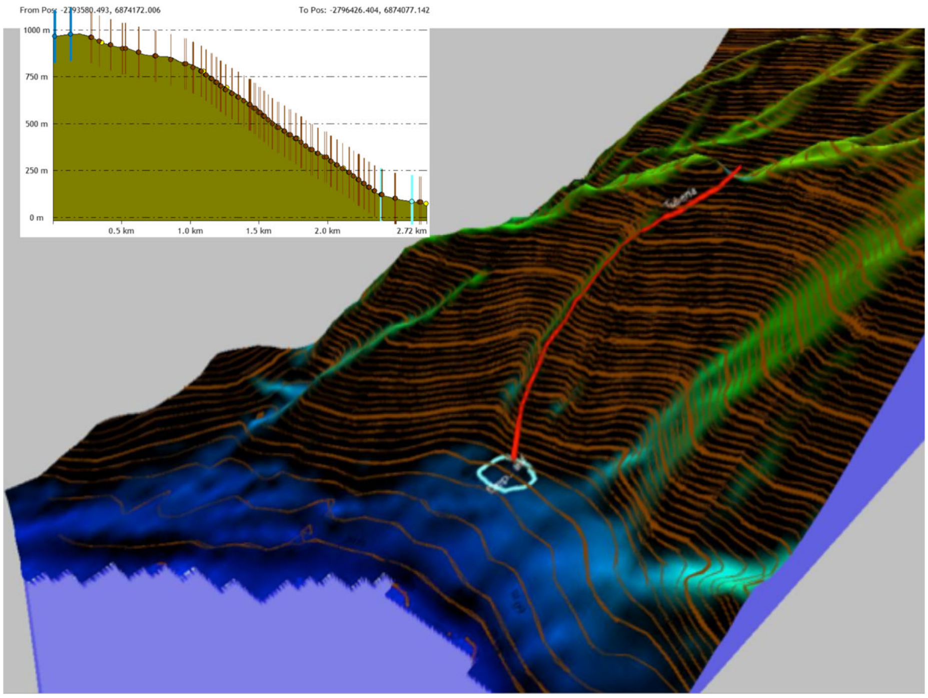

Fig. 6 3D map of the selected PHES site together with the elevation contour

map of the site. It is located in the Coastal Cliff, close to the Wind Farm location.

Our choice for the turbine system is the use of two Pelton turbines with one injector that can work in parallel to provide the maximum power. The Pelton turbines can work up to 10% of the nominal load, have efficiencies around 90% and are adequate for the site height differences and required nominal flows. The turbines will be coupled to two generators with nominal power 5 MW, AC output voltage of 6 kV and 98% efficiency.

Regarding the pumping system configuration, our choice is the use of multistage centrifugal pumps: 6 of 2 MW and 2 of 0.5 MW. To simplify the calculations an efficiency of 90% for all loads is considered. The motors that drive the pumps work at 6 kV with an efficiency of 98%.

Steel penstocks have rugosities of ∼0.6 mm. The hydraulic losses are calculated using standard formulas for different pipe diameters. For each case, the nominal flow rate in production and storage mode is calculated by solving iteratively Eq. 13/Eq. 14. The hydraulic losses drop below 5% in both modes at nominal conditions for a tube diameter of 0.85 m. Losses because of other hydraulic components like valves, bypasses, contractions/expansions, etc. are small (10% of Penstock losses) and taken into account. Table 5 gives the final nominal flow rate and hydraulic losses in both modes. Using these calculations the storage efficiencies s_1 and s_2 are calculated.

The penstock wall thickness required to withstand the hydrostatic pressure is given by:

$$e[m] = \frac{D\,P}{2\,\sigma_f\,K_f} + e_s \tag{15}$$

where e_s is extra thickness in meters to allow for corrosion, k_f is the weld efficiency (0.9), D is the pipe diameter in meters, σ_f is the allowable tensile stress in Pascals (1400 kgf/cm^2, i.e., 1.373 10^5 Pa) and P is the hydrostatic pressure in Pascals. Since the hydrostatic pressure changes from the upper to the lower reservoir, the penstock is

Table 5 Nominal flow rate and hydraulic losses at nominal load for production and storage

	Production	Storage
P (MW)	8.5	14
δh_g	850	850
l Penstock (m)	2500	2500
D Penstock (m)	0.85	0.85
Q_e m^3/s	1.21	2.0
V m/s	2.10	3.50
Hydraulic losses (Penstock) (m)	12.5	33.0

Table 6 Assumed PHES investment cost

Total	23,310,000 *e*	100%
Hydraulic sub-system	8,420,000 *e*	36%
Penstocks	1,500,000 + 2,420,000 *e*	17%
Reservoirs	2 x 1,400,000 *e*	12%
Water intake/valves	700,000 *e*	3%
Water supply	1,000,000 *e*	4%
Electromechanical sub-system	9,830,000 *e*	42%
Turbines	1,200,000 *e*	5%
Generators	850,000 *e*	3.5%
Pumps and motors	4,250,000 *e*	18%
Control system	1,200,000 *e*	5%
Transport/installation	1,930,000 *e*	8%
Engineer	400,000 *e*	1.5%
Civil works	3,260,000 *e*	14%
Central building	1,260,000 *e*	5%
Access roads	2,000,000 *e*	9%
Engineer and reserve	1,800,000 *e*	8%

built in sections of 100 m with decreasing thickness (10–30 mm). The total weight of the penstock is ∼1000 tons.

The surge pressure for the water-hammer effect at the pumping nominal load is 450 m, which would require a substantial increase of the thickness walls that would yield to a doubling of the total penstock weight, i.e. its cost. For that reason, the installation of a surge tower or relief valves is necessary.

The free parameter of the design is the maximum storage capacity, E_{MSC} MWh. For a given value of E_{MSC}, the volume of the water reservoirs is calculated by multiplying the flow rate in generation mode by $E_{MSC}/8.5$ h, adding a 20% safety margin. In the selected site, there is room for reservoirs with storage capacities up to 1000 MWh.

The reservoirs will be constructed following the scheme of an Earth/Rock filled dam. The depth of the reservoir will be 14 m, leaving 1.3 m between the maximum water level and the top of the dam. The digged material will

Table 7 Electrical infrastructures required for the PV-Wind-PHES energy system, together with the cost estimation

Total		3,460,000*e*
Transf. 24 MVA 20–66 kV	PV	800,000*e*
Transf. 18 MVA 6–66 kV	PHES	600,000*e*
Transf. 10 MVA 66–23 kV	Paranal	300,000*e*
10-km cable line	PV-Paranal	800,000*e*
12-km cable line	PHES-Paranal	960,000*e*

be reused to build the trapezoidal perimetral dike (3:1), which fixes the dimensions of the reservoir. The surface in contact with the water and the air-water layer is covered by a geotextile cloth.

To build and maintain the upper reservoir it is necessary to construct a 12 km access road. In the case of the lower reservoir there is a nearby access road, so only a short and flat connection to it is necessary. It will be also necessary to build a housing for the electromechanical equipment.

Cost estimation

The total cost after 25 years of the wind-solar PV plant with PHES storage is estimated using Eq. 2. The CAPEX in that equation has the following components:

- Solar PV and wind plant: total power installed times a unitary cost of 1,700*e*/kW.
- PHES: the cost of a PHES system with E_{MSC}=110 MWh is estimated to be 26.4 M*e*. Table 6 shows a breakdown. The PHES cost for different values of E_{MSC} is estimated using:

$$\frac{E_{MSC}}{110} C_1 + C_2 \tag{16}$$

  where C_1=3.8 M*e* is the baseline cost of water and reservoir and C_2=19.51 M*e* is the cost of the rest of the subsystems.
- Back up system: 8.5 M*e*.
- Electrical infrastructures: 3.5 M*e*, see Table 7.

The OPEX has the following components:

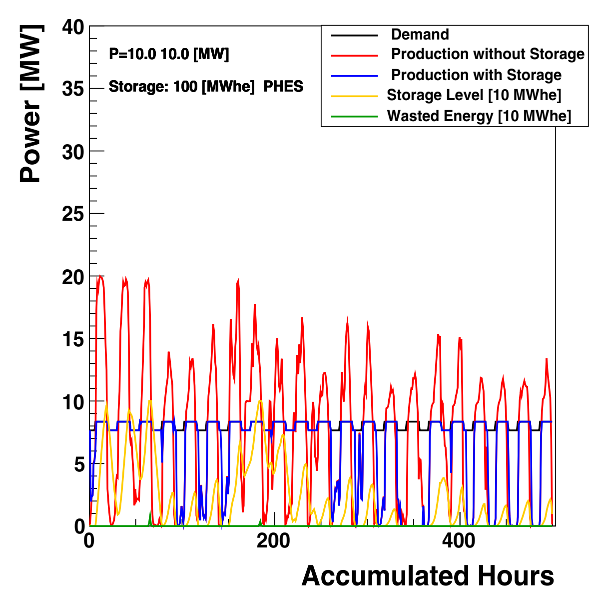

Fig. 7 An example of the time series of electricity production for P_{total}=20 MW, f_{solar}=0.5 and E_{MSC}=100 MWh

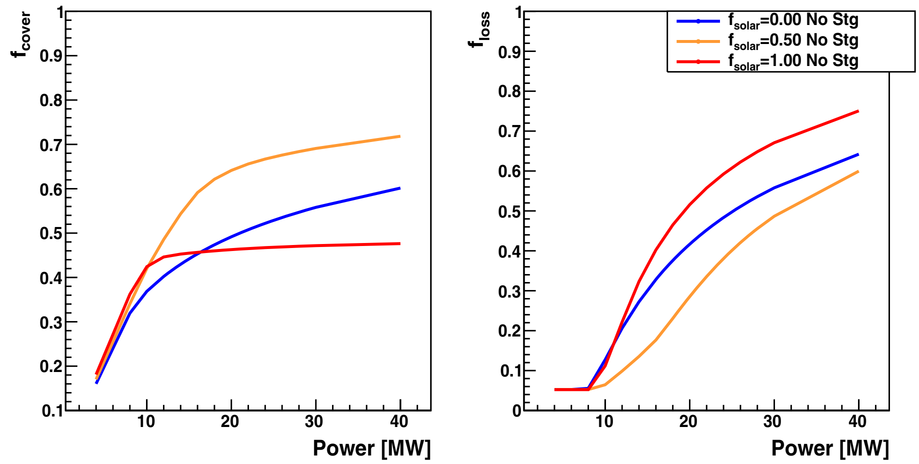

Fig. 8 f_{cover} and f_{loss}^{All} as a function of the total installed power for E_{MSC}=0 MWh and three cases of f_{solar}, 0, 0.5, and 1

- Insurance and O&M: we assume 2% of CAPEX with 3% inter annual increase.
- Gas purchases: $(1 - f_{cover})\cdot 70$ GWh times the unitary price given by Eq. 1.
- Solar PV: the required annual enhancement of the power installed to reach the same nominal production as the first year [5].

Results

The electricity production is simulated for the following parameters:

- P_{total} MW : 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, and 40.
- f_{solar}: 0, 0.25, 0.5, 0.75, and 1.
- E_{MSC} MWh: 0, 20, 40, 60, 80, 100, 120, 240, 480, 1000.

An example of the time series is shown in Fig. 7 for P_{total}=20 MW, f_{solar}=0.5 and E_{MSC}=100 MWh. For each simulated case, the annual value of f_{cover} and f_{loss}^{All} is calculated. The left (right) panel in Fig. 8 show an example: f_{cover} (f_{loss}^{All}) as a function of the total installed power for E_{MSC}=0 MWh and three cases of f_{solar}, 0, 0.5, and 1. For this value of E_{MSC}, the optimum system in terms of coverage is neither purely wind or solar, but a mixture. f_{loss}^{All} for small P_{total} is due to availability and transport.

On the basis of the costs shown in Table 2, we select two target maximum costs: 100 and 130 M*e*. For each simulated case, the total cost over 25 years is calculated as in "Cost estimation" section. The case with a cost below the target and with maximum coverage is kept. The two cases selected for the two targets are shown in Table 8. The coverage factors are as large as 64 and 88%. It should be mentioned that the losses for the high cost target are driven by the storage efficiency, transport losses, and availability.

Finally, the case of a concentrated solar power (CSP) plant with thermal energy storage is analyzed. This technology is considered separately since the storage system cannot be used simultaneously by the Wind farm [6]. The design and costs are presented in Appendix. The total cost is 124 M*e* and f_{cover} 72.5%. This alternative is within the high cost target, but it has lower coverage factor than the case presented in this section.

Endnotes

[1] I_0 is only 12% smaller than the irradiance outside the atmosphere (1370 W/m^2), which is an indicator of the quality of the site.

[2] The electricity production using the model and the raw data for the reference year agrees within 5%.

[3] α=0.08 from the ratio of the measurements at 10 and 30 m. A conservatively smaller value is taken: measurements at 10 m can be affected by the surrounding buildings

[4] According to our estimations, it can be severe, reducing the water level by almost 3 m per year.

Table 8 The selected systems for the two budget thresholds

	100 M*e*	130 M*e*
f_{solar}	0.5	0.75
P_{total} MW	20	24
E_{MSC} MWh	0	120
f_{cover}	64%	88%
f_{loss}^{All}	29%	20%
f_{loss}^{Stg}	24%	5%
Total cost M*e*	100.0	128.0

[5] It is calculated assuming: PV system prices will decrease at a rate of 20% over 25 years; PV module degradation is 20% over 25 years.

[6] Electricity from the Wind Farm would have to be converted into thermal energy. To convert back to electricity the efficiency is given by the steam turbine, ∼32%.

Appendix

Concentrated solar power (CSP) plant with thermal energy storage

The CSP is a technology that needs to be considered when there is plenty available land, the cloudy fraction is small and the fraction of direct irradiance is high. The dessert characteristics of the site fulfill these three criteria. The technology considered in this work is the parabolic trough collectors (PTC), widely considered in a stage of maturity.

In a CSP plant, an oil is heated in the solar field from 293 ^{o}C to 393 ^{o}C and sent either to the thermal storage system or to a heat exchanger that produces water vapour at 380 ^{o}C and 104 bar. The vapour is then conducted to a steam turbine coupled to a generator. After the turbine, the vapour is taken to a condenser and fed again into the loop. Due to the scarcity of water in the site, aerocondensers are considered. The efficiency to convert thermal energy into electricity depends on the nominal power of the turbine and for a 10 MW steam turbine is ∼32%.

The solar field is an array of PTCs. The mirrors have a one axis tracking system (North-South) that ensures that at all moments the solar vector lies within the plane perpendicular to the aperture of the collector. Alignment is a strong requirement in PTCs, and also cleaning.

The PTCs have lengths between 100 and 150 m. The 8 module EuroTrough collector with PTR-70 Schott tubes is selected. N_{series} of these modules are placed in series to form a group. $N_{parallel}$ groups are connected in parallel in *central feeding configuration* to minimize pipe lengths. The separation between rows of collectors is three times the width of the parabola to ensure that annual shadowing losses are below 1%.

The thermal power captured by the collector is given by:

$$P_{collector}[W] = A_c\, I_D \cos\Phi\ \eta_{opt\phi=0^0}\ K(\Phi)\ F_e - P_{losses} \tag{17}$$

where $\eta_{opt\phi=0^0}\ K(\Phi)$ is a parameterization of the optical and geometrical losses of the collector, A_c is the aperture area, I_D is the direct irradiance in W/m^2 at the period considered, F_e is a factor that takes into account the dirt in the mirrors (0.95), and P_{losses} are the thermal losses parameterized with its dependence on the temperature difference between the fluid and the ambient, as well as on the direct irradiance and incidence angle.

The collected power can also be written as:

$$P_{collector}[W] = Q_m \int_{T_{in}}^{T_{out}} C_p dT \tag{18}$$

where Q_m is the fluid mass flow in kg/s, C_p is the specific heat in J/K Kg and T_{in}/T_{out} is the start/final temperature of the fluid. The thermal fluid chosen is an oil called Therminol VP1. Its maximum working temperature is 398^o and solidification temperature is 12^o. This fluid has to be pressurized to 10.5 bar so it is not gas phase at the maximum working temperature. The specific heat and density depends on temperature and is taken from a parameterization provided by the manufacturer.

N_{series} of collectors have to rise the fluid temperature from T_{in}=293 ^{o}C to T_{out}=393 ^{o}C. The necessary value of Q_m is calculated iteratively by equating Eqs. 17 and 18 in 1 m intervals.

The fluid must circulate in a regime turbulent enough to avoid thermal gradients between the external/internal face of the tube that can cause fractures. The optimum value of N_{series} is calculated by imposing a condition on the Reynolds number of the circulating fluid for the time of maximum direct irradiance. In our design, N_{series} must be 4.

The hydraulic losses are calculated for each configuration of the system (N_{series}, $N_{parallel}$) and time period considered using the oil and tube characteristics and ambient conditions. Losses in the pipes that connect the collectors with the heat exchanger and the losses in the pump are also taken into account.[7].

The required electrical pumping power is given by:

$$P_{pump}[W] = \Delta P\ [Pa]\ \frac{N_{parallel}\ Q_m\ [kg/s]}{\rho[kg/m^3]} \frac{1}{\eta_m \eta_e} \tag{19}$$

where η_m (∼ 70%) and η_e (∼99%) are the mechanical and electrical efficiency of the pump.

Table 9 CSP design parameters and annual results

N_{series} and $N_{parallel}$	4 and 33
f_{cover} (Design period)	100%
Maximum storage capacity	100 MWh/312 MWth
Volume of hot/cold tanks	4618/4471 m^3
f_{cover} (year)	72.5%
f_{loss}^{Eff} (year)	2.8%
f_{loss}^{Stg} (year)	<1%
$f_{loss}^{Transport}$ (year)	1.2%
$f_{loss}^{Availability}$ (year)	3.6%
Land footprint	∼432 *x* 594 m ∼0.25 km^2
Net mirror aperture	72138 m^2
Occupancy ratio	30%

Table 10 Electrical infrastructures required for the CSP plant

Total		1,400,000*e*
Transf. 10 MVA 20–66 kV	CSP plant	300,000*e*
Transf. 10 MVA 66–23 kV	Paranal	300,000*e*
10-km cable line	PV -Paranal	800,000*e*
t_1, t_2, t_3	N/A, N/A, 2%	

The electrical power produced by the plant is given by:

$$P_P[W](t) = \eta\, N_{series}\, N_{parallel}\, P_{collector}(t) - P_{pump}(t) \quad (20)$$

where η is the efficiency to convert thermal to electrical energy (32%). The storage efficiencies considered are s_1=s_2=96% (Round trip efficiency of 92%). Transport losses are only applicable to t_3 (2%). The availability is included as described before.

The electricity production described in "Electricity production time series: methodology" section is calculated in 10 min intervals during a period of 48 hours around the summer solstice. $N_{parallel}$ is increased until f_{cover}=100%. The required value of $N_{parallel}$ is 33. E_{MSC} is given by the maximum storage level during the design period (100 MWh).

The storage system must be able to store 100 MWh, i.e., 312 MWth. This capacity is increased by a safety margin of 8%, i.e., 337.5 MWhth. The temperature in the hot/cold tank corresponds to the temperature of the oil before/after the heat exchanger. Nitrate salt (60% by weight $NaNO_3$ and 40% KNO_3) is considered as storage medium. The mass required can be calculated using:

$$Q[J] = m \int_{T_{min}}^{T_{max}} C_p dT \quad (21)$$

which yields 8530 tons of salt to store 337.5 MWth. The corresponding volume of the hot and cold tank is different due to temperature. The volume required for the cold/hot tank is 4471 and 4618 m^3. Fast fluctuations of the solar resource are easily tracked by the thermal storage system by controlling the flow from the solar field that is diverted to the heat exchanger of the storage system.

Table 11 CSP investment cost breakdown

Solar field	17,000,000 *e*	29%
Power system	10,000,000 *e*	17%
Storage system	15,000,000 *e*	26%
Heat transfer system	6,700,000 *e*	11.5%
Aerocondensers	3,000,000 *e*	5%
Other (engineer/reserve, etc.)	6,700,000 *e*	11.5%
Total	58,500,000 *e*	100%

The electricity production is then calculated for the whole year. The results are shown in Table 9 together with the main design parameters.

A flat area is necessary to ease installation of the solar field. A possible site has been found 10 km away from Cerro Paranal. The access road to the Cerro Paranal passes by the solar field, so no extra civil works are planned. For electrical infrastructures and their cost, see Table 10.

The investment cost (CAPEX) of the CSP plant is estimated to be 58.5 M*e*. Table 11 shows the breakdown. The OPEX considered is 2% of the CAPEX with a 3% inter annual increase. The total cost after 25 years normalized to year 0 is 124 M*e*.

Abbreviations

BTU: British thermal unit; CAPEX: Capital expenditure; CCGT: Combined cycle gas turbine; CSP: Concentrated solar power; CTA: Cherenkov telescope array; E-ELT: European extremely large telescope; ESO: European southern observatory; MUSD: Million US dollars; OpenWind: Open software to design Wind Farms; OPEX: Operating expenditure; PHES: Pumped hydro energy storage; PV: Photovoltaic; PTC: Parabolic Trough Collectors; SIC: Sistema interconectado central; SING: Sistema interconectado del Norte Grande; STATCOM: Static synchronous compensator; VLT: Very large telescope; WASP: Wind energy industry-standard software; WRG: Wind Resource Map (Power density); k: Interest rate; I_G: Global solar irradiance in a surface W/m^2; I_D: Direct irradiance in the sun direction; f_d: Diffuse irradiance in a surface expressed as a fraction of the direct irradiance; Φ: Angle subtended by the normal of a surface with the sun direction; θ_s: Solar zenith angle; τ: Atmospheric extinction parameter; $P_P(t)$: Time series of power produced by solar/wind plant in MW; $P_D(t)$: Time series of power demand in MW; $P_A(t)$: Time series of power available to satisfy the demand in MW; E_P,E_D and E_A: Annual sum P_P,P_D and P_A E_S and E_{MSC}: Storage Level and Maximum Storage Capacity in MWh; $P^{to\ store}$ and $P^{to\ store}_{max}$: Power to store and Maximum Instantaneous Power that the storage system is able to store; s_1/s_2: Efficiency of the storage system to store/deliver electricity; $t_1/t_2/t_3$: Transport efficiencies (transformer and lines) between solar/wind plant-storage system (t_1), storage system-demand site (t_2) and solar/wind plant-demand site (t_3); E^{Stg}_{loss}: Energy lost during storage operations due to $P^{to\ store}_{max}$ and E_{MSC}; E^{Eff}_{loss}: Energy lost during storage operations due to s_1/s_2; $E^{Transport}_{loss}$: Energy lost due to transport inefficiencies; E^{Avail}_{loss}: Energy lost due to operation and maintenance (availability); f_{cover}: E_A/E_D energy coverage; f^{Stg}_{loss}: E^{Stg}_{loss}/E_P, energy loss due to storage size and storage maximum power; f^{All}_{loss}: $(E^{Stg}_{loss}+E^{Eff}_{loss}+E^{Transport}_{loss}+E^{Avail.}_{loss})/E_P$, total energy loss; I_{stc}: The irradiance in standard conditions 1000 W/m^2; W_p: Watt Peak, solar panel power for I_{stc}; T_{stc}: The solar panel temperature in standard conditions (25^oC); $f_{therm.}$, $f_{shading}$, f_{cte}: Solar panel losses, thermal, shading and those that do not depend on solar irradiance; g: Solar panel thermal loss coefficient; $V_{op,inv}$: Inverter input voltage range; $V_{mpp,panel}$: Solar panel volage at maximum power; v_{hub}: Wind speed at hub height; α: Wind speed height coefficient; ρ_{air}: Air density; ρ: Water density; g: Gravity acceleration constant; Q: Water flow rate through the penstocks in m^3/s; δh_n: Net height difference between upper and lower reservoir in a PHES; δh_g: Gross height difference; $\delta_h(Q)$: Q dependent hydraulic losses; η_{turb}, η_{gen}, η_{pump}, η_{mot}: Efficiencies of turbine, generator, pump and motor in a PHES; P_h: Hydro power; P_e: Electrical power; D: Penstock diameter; l: Length of penstock; k_f: Penstock weld efficiency; σ_f: Allowable tensile stress in Pascals; P: Hydrostatic pressure in penstock; P_{losses}: PTC thermal losses; F_e: PTC losses due to dirtying; $P_{collector}$: Thermal power captured by a PTC; $\eta_{opt\phi=0^0}$ $K(\Phi)$: Optical and geometrical losses of the collector; C_p: Specific heat of PTC thermal fluid; Q_m: Mass flow in kg/s of the thermal fluid; T_{in}/T_{out}: Temperature in/out of the thermal fluid

Acknowledgements

This work would not be possible without the financial support of the CNPq, FAPESP (PROCESSO 2015/15897-1) and the resources of the Instituto de Física de São Carlos. We thank Vitor de Souza for the careful reading of the manuscript, Eduardo Zarza for his guidance with CSP technology, Marcos Blanco for providing the WASP simulations needed to estimate the Wind

Resource, Marc Sarazin for his help with the Wind data and ESO water supply, and Natalia Serre for all the information she provided concerning CTA power supply. Finally, we also thank all the Escuela de Organizacion Industrial (EOI) staff for their support.

Authors' contributions

All authors contributed to the development of the work. The corresponding author prepared the manuscript, but all authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Received: 25 November 2016 Accepted: 10 February 2017
Published online: 06 March 2017

References

1. Towards a Green Observatory. https://www.eso.org/sci/libraries/SPIE2010/7737-73.pdf. Accessed Feb 2017
2. The E-ELT construction proposal. http://www.eso.org/public/products/books. Accessed Feb 2017
3. Comision Nacional de Energia de Chile. www.cne.cl. Accessed Feb 2017
4. Ministerio de Energía de Chile. http://antiguo.minenergia.cl. Accessed May 2015
5. European Southern Observatory. http://archive.eso.org. Accessed Feb 2017