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Q1. Resources: Consumption, Production, Capacity

Coal	Present Chilean Consumption		0.28*10^18 (Joules/year)[1]
Natural Gas	Present Chilean Consumption		0.23*10^18 (Joules/year)[1]
Oil	Present Chilean Consumption		0.76*10^18 (Joules/year) [1]
Nuclear	Present Chilean Consumption		0 (Joules/year)[2]
Hydroelectricity	Present Chilean Consumption		0.19*10^18 (Joules/year) [1]
Renewables	Present Chilean Consumption		0.19*10^18 (Joules/year) [1]
Coal	Present Chilean Production	2529*10^3 ST[3]	5.5*10^13(Joules/year)
Natural Gas	Present Chilean Production	1750 million m^3[4]	6.7*10^16 (Joules/year)
Oil	Present Chilean Production	2833 barrels/day[5]	0.715*10^16 (Joules/year)
Nuclear	Present Chilean Capacity		0 MW[2]
Hydroelectricity	Present Chilean Capacity		6700 MW[6]

[1] BP Statistical Review 2020
[2] https://www-pub.iaea.org/MTCD/Publications/PDF/cnpp2018/countryprofiles/Chile/Chile.htm (No nuclear plants in Chile)
[3] https://knoema.com/atlas/Chile/topics/Energy/Coal/Primary-coal-production
[4] https://www.ceicdata.com/en/indicator/chile/natural-gas-production-opec-marketed-production
[5] https://www.ceicdata.com/en/indicator/chile/crude-oil-production#:~:text=Chile's%20Crude%20Oil%3A%20Production%20was,to%202019%2C%20with%2060%20observations.
[6] https://www.evwind.es/2020/07/07/the-global-hydropower-installed-capacity-is-1150-gw/75616

Wind	Present Chilean Capacity	1621 MW[7]
Solar	Present Chilean Capacity	2720 MW (April 2020) [8]
Bio-Energy	Present Chilean Capacity	501 MW (April 2020)[8]
Geo-Thermal	Present Chilean Capacity	40 MW(April 2020)[8]

Q2. Fossil Energy and Carbon Sequestration

a.

Total electricity is 83.9 TWh/yr

Coal accounted for roughly 37% of total electricity generated (Given)

Thus, Electricity from coal, $E = 83.9 * 0.37 \frac{TWh}{year} = 31.043 \frac{TWh}{year}$

Number of households, $n = \frac{31.043*10^9}{12908} = \boldsymbol{2.40\ million\ households}$

b.

Assumed efficiency for typical Rankine cycle power plants= 0.42 [9]

$P_{coal} = \frac{P_E}{0.42} = 73.91\ billion \frac{kWh}{year} = 73.9 * 10^{12} \frac{W}{year} = 73.9 * 10^6 \frac{MWh}{year}$

Coal releases 95.35 kg CO2/million BTU [10] or 0.09535 ton/MBTU

1 BTU = 2.9*10^-7 MWh

So, $\frac{0.09535}{10^6} * \frac{1}{2.93*10^{-7}} = 0.325\ tonne \frac{CO_2}{MWh}$

The emissions are: $Emissions = 73.9 * \frac{10^6 MWh}{year} * 0.325 = 24.021 * 10^6 \frac{tonnes}{year}$

Coal Gas	Current GHG Emissions	24.021 *10^6 Metric tons CO_2/year

c.

Typical values of forestation:

[7] https://www.statista.com/statistics/758797/installed-wind-power-generation-capacity-chile/
[8] https://www.statista.com/statistics/757163/installed-renewable-power-generation-capacity-source-chile/
[9] Wikipedia: Rankine Cycle
[10] https://www.eia.gov/environment/emissions/co2_vol_mass.php

$P_e = 31.043 * 10^9 \frac{kWh}{year}$

$e_{ng,yr} = 24.021 * \frac{10^9\ kg}{year}$

$C_{for} = 25 * 10^{-3} \frac{\$}{kg}$ (Standard value)

$LCOE_{for} = (e_{ng,yr} * C_{for})/(P_e)$

$LCOE_{for} = \frac{24.021*10^9*25*10^{-3}}{31.043*10^9} = \mathbf{0.019} \frac{\$}{\mathbf{kWh}}$

$LCOE_{new} = LCOE_{initial} + LCOE_{for} = 0.019 + 0.04 = \mathbf{0.059} \frac{\$}{\mathbf{kWh}}$

For 3-5:

	Annual Power Output (MWh/year)	Annual Power Output (Households)	LCOE ($/kWh)	# Required Plants
Coal + Forest	31.043 * 10^6	2404942	0.059	---
Geothermal	0.67*10^6	51905	0.068	84
Solar PV	0.285*10^6	22079	0.030	197
Solar PV + Storage	0.396*10^6	30679	0.16	141
Wind	2.3*10^6	178184	0.034	24

Coal in 2019: 31.043 TWh/year

The total electricity has been growing at 3% every year for the past decade decade.

Expected electricity due to coal in 2040: $E = 31.043 * (1.03)^{20} = 56.067 \frac{TWh}{year}$

<u>3. LCOE and IRR: Geothermal</u>

Discount rate=10%, N=30

Annual capacity, $C = 81 * 0.95 * 24 * 365 \frac{MWh}{year} = \mathbf{0.67} * \mathbf{10^6} \frac{MWh}{year}$

Number of households, $N = \frac{0.67*10^9}{12908} = \mathbf{51905}\ households$

Annualized value of NPV:

$A_{plant} = P_{plant} * \frac{i(i+1)^N}{(i+1)^N - 1} = 420 * 0.106 = 44.52\ million$

Annualized cost of decommissioning:

$A_{dec} = P_{dec} * \frac{i}{(i+1)^N - 1} = 1 * 0.006 = 0.006\ million$

O&M:

Cost: 0.2 cents/kWh = 0.002 $/kWh

$A_{O\&M} = 0.002 * 0.67 * 10^3 = 1.34\, million$

Fuel: Cost= 0

Profit: 0

Total annualized cost, $Cost = 44.52 + 0.006 + 1.34 = 45.866\, million$

$LCOE = \frac{45.866*10^6}{0.67*10^9} = \mathbf{0.068}\ \$/\boldsymbol{kWh}$

Number of plants required in 2040:

$n_{plants} = \frac{Total\ electricity\ requirement}{Annual\ capacity} = \frac{\left(56.067*10^6 \frac{MWh}{year}\right)}{0.67*10^6 \frac{MWh}{year}} \sim \mathbf{84\ plants}$

<u>4. LCOE and IRR: Capacity factor, PV, and storage</u>

1 hectare = 10000 m^2

550000 solar panels have been installed with 420 hectares (Assume this to be the incident area)

Total solar area= 4.2*10^6 m^2

Insolation (GHI) ~ 7 kWh/m^2/day

$\eta = 0.203$ [11]

Area of each solar panel=2 m^2 [12]

Total incident area=2*550000=1100000 m^2

Incident Energy per year, $E = 365 \frac{day}{year} * (1.1 * 10^6)\, m^2 * 7 \frac{kWh}{m^2 day} = 2.81 * 10^6 \frac{MWh}{year}$

Actual Energy per year, $E = 0.203 * 2.81 * 10^6 = 0.57 * 10^6 \frac{MWh}{year}$

Maximum energy$=145 * 24 * 365 = 1.27 * 10^6 \frac{MWh}{year}$

a.

Not including capacity credit:

Capacity factor, $C = \frac{0.57*10^6}{1.27*10^6} = \mathbf{0.45}$

b. Grid without storage: CC=0.5

[11] https://www.lg.com/us/business/solar-panels/lg-lg395n2w-v5

[12] Homework 5, 39610

Electricity generated, $E = 0.5 * 0.57 * 10^6 = \mathbf{0.285 * 10^6} \frac{MWh}{year}$

Number of households, $N = \frac{0.285*10^9}{12908} = \boldsymbol{22079\ households}$

c. Grid with storage, CC=0.75

112 MW is derived from storage systems

Electricity due to storage systems, $E_{storage} = 112 * 365 * 24 * 0.45 = 0.44 * 10^6 \frac{MWh}{year}$

Electricity due to solar PV, $E_{solarPV} = (145 - 112) * 365 * 24 * 0.45 = 0.13 * 10^6 \frac{MWh}{year}$

Taking into account the capacity to grid factor:

$$E = (0.75 * 0.98 * 10^6 + 0.5 * 0.29 * 10^6) * capacity\ factor = 0.88 * 10^6 * 0.45 = \mathbf{0.396 * 10^6} \frac{MWh}{year}$$

Number of households, $N = \frac{0.396*10^9}{12908} = \mathbf{30679}\ households$

d. LCOE without storage

Discount rate=10%, Lifetime=20 years, NPV=175 million

Annualized value of NPV:

$A_{plant} = P_{plant} * \frac{i(i+1)^N}{(i+1)^N - 1} = 175 * 0.106 = 7.95\ million$

Annualized cost of decommissioning:

$A_{dec} = P_{dec} * \frac{i}{(i+1)^N - 1} = 0.5 * 0.017 = 0.0085\ million$

O&M:

Cost: 0.2 cents/kWh = 0.002 $/kWh

$A_{O\&M} = 0.002 * 0.285 * 10^3 = 0.57\ million$

Fuel: Cost= 0

Profit: 0

Total annualized cost, $Cost = 7.95 + 0.0085 + 0.57 = 8.53\ million$

$LCOE = \frac{8.53*10^6}{0.285*10^9} = \mathbf{0.030}\ \$/\boldsymbol{kWh}$

e. LCOE with storage

Annualized value of NPV:

$A_{plant} = P_{plant} * \frac{i(i+1)^N}{(i+1)^N - 1} = 175 * 0.106 = 7.95\ million$

Annualized cost of decommissioning:

$$A_{dec} = P_{dec} * \frac{i}{(i+1)^{N}-1} = 0.5 * 0.017 = 0.0085\ million$$

O&M:

Cost: 0.2 cents/kWh = 0.002 $/kWh

$$A_{O\&M} = 0.002 * 0.396 * 10^{3} = 0.792\ million$$

Fuel: Cost= 0

Profit: 0

Levelized storage cost= (108+140)/2= 124 $/MWh[13]

Cost of storage, $C_{storage} = 124 * 0.44 * 10^{6} = 54.56$

Total annualized cost, $Cost = 7.95 + 0.0085 + 0.792 + 54.56 = 63.31\ million$

$$LCOE = \frac{63.31*10^{6}}{0.396*10^{9}} = \mathbf{0.16}\frac{\$}{\boldsymbol{kWh}}$$

f. Number of plants,$n_{plants} = \frac{Total\ electricity\ requirement}{Annual\ capacity} = \frac{\left(56.067*10^{6}\frac{MWh}{year}\right)}{0.285*10^{6}\frac{MWh}{year}} \sim \mathbf{197\ plants}$

g. Number of plants,$n_{plants} = \frac{Total\ electricity\ requirement}{Annual\ capacity} = \frac{\left(56.067*10^{6}\frac{MWh}{year}\right)}{0.396*10^{6}\frac{MWh}{year}} \sim \mathbf{141}\ plants$

5. LCOE and IRR: Wind

The wind has velocity of 7 m/s.

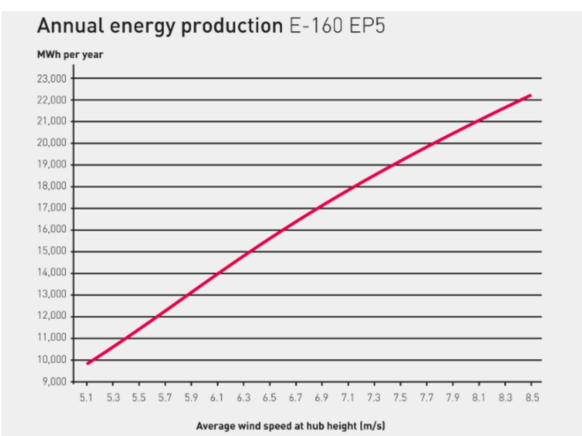

Figure 1: Power curve for the turbine[14]

At 7m/s, annual energy production ~ 17500 MWh/year

[13] https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf
[14] https://www.enercon.de/en/products/ep-5/e-160-ep5/

Thus, for 132 turbines, total energy production, $E_{prod} = 132 * 17500 = 2.3 * 10^6 \frac{MWh}{year}$

Nameplate capacity is 607 MW.

Thus, maximum production possible, $E_{max} = 607 * 24 * 365 = 5.3 * 10^6 \frac{MWh}{year}$

Capacity factor, $C = \frac{E_{prod}}{E_{max}} = \frac{2.3*10^6}{5.3*10^6} \sim \mathbf{0.43}$

Number of households, $N = \frac{2.3*10^9}{12908} \sim \mathbf{178184\ \boldsymbol{households}}$

LCOE:

Lifetime= 30 years, Discount rate=10%

Annualized value of NPV:

$$A_{plant} = P_{plant} * \frac{i(i+1)^N}{(i+1)^N - 1} = 700 * 0.106 = 74.2\ million$$

Annualized cost of decommissioning:

$$A_{dec} = P_{dec} * \frac{i}{(i+1)^N - 1} = 1 * 0.006 = 0.006\ million$$

O&M:

Cost: 0.2 cents/kWh = 0.002 $/kWh

$$A_{O\&M} = 0.002 * 2.3 * 10^3 = 4.6\ million$$

Fuel Cost=0

Profit=0

Total annualized cost, $Cost = 74.2 + 0.006 + 4.6 = 78.806\ million$

$$LCOE = \frac{78.806*10^6}{2.3*10^9} = \mathbf{0.034}\ \$/\boldsymbol{kWh}$$

Number of plants required in 2040:

$$n_{plants} = \frac{Total\ electricity\ requirement}{Annual\ capacity} = \frac{\left(56.07*10^6 \frac{MWh}{year}\right)}{2.3*10^6 \frac{MWh}{year}} \sim \mathbf{24\ \boldsymbol{plants}}$$

6. <u>Comparative Technologies: Recommendations</u>

Coal:

Based on the calculations, coal has a low LCOE of 0.059 $/kWh. Moreover, the power output from coal + forestation is very high, as it powers close to 2 million households. Currently, 37% of the electricity comes from coal, which is a significantly high number. Chile has plans to phase out coal plants by 2040 and based on the calculation, it would require a significant number of geothermal or renewable plants to be set-up. A policy I'd recommend for continued coal + Forestation is to keep producing the coal at a steady rate, retiring coal power plants at a constant rate as that of new power plants being added. This would ensure that the demand constraints are met and also helping Chile to attain their goal of lower GHG emissions.

Geothermal:

For the geothermal plant proposed in the problem, it can roughly power around 50k households. To mimic the coal power plant behavior, around 86 such plants need to be constructed over the next 20 years. This is assuming that no one source is being used to cater to the growing demand. Chile has a huge geothermal potential (~16 GWe) which should be utilized to maximum extent possible. Also, considering the investments for the next 30 years, LCOE is around 0.067 $/kWh, a tad bit higher than the coal cost of electricity. This implies that using geothermal has a strong potential to cater to the needs of Chile in the long run that is to be carbon neutral by 2050.

Solar:

Based on the calculations, a single solar farm can power around 30k households with a much lower LCOE than geothermal and coal. Chile has suitable locations to use for solar energy such as the Atacama Desert, which receives the maximum annual solar radiation. Such areas in Chile can be rampantly used for solar energy production. Chile has set up a short-term goal of generating 20% of its energy from renewables, so, the governing body should incentivize solar energy production till 2025, until other sources of energy such as geothermal and hydropower are being developed.

Solar with storage:

Solar with storage has an advantage of using energy as per the demand in the grid and is prone to demand fluctuations. However, the LCOE of solar storage is much higher than that of the other sources of energy. This option would prove useful wherein the energy demand is not steady and has a fluctuating behavior. Also, as the LCOS is very high, it would then be translated to the price of electricity. A good option would be to encourage using solar with storage in areas with higher-income neighborhoods and urban areas, which could bear the added cost of storage for electricity.

Wind:

Chile has a huge wind energy potential (that of 40GW in the future). This potential is more than that of hydropower, geothermal and even solar. Moreover, construction of 10-15 wind farms on suitable sites can also help in achieving the goals of phasing out peakers by 2040 and achieve its 70% target of renewables. However, the deterrent here is the humungous cost involved in setting up a plant (~700 million) which requires heavy resource allocation by the Chilean authorities. Wind power plants can thus be developed intermittently till 2050, depending upon the country’s budget.

Summary:

Chile, as a country has set up progressive goals to promote renewable energy across the country, with a motive to reduce its GHG emissions. A combined policy which I’d suggest based on the analysis is that: In the short term, coal should be retired at a constant rate which ramping up the use of solar energy systems. In the long run, geothermal and wind power would thus support the hydropower with a motive of achieving 70% renewable energy by 2050.