Renewable Energy Technologies I

# Exercise 2

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## Instructions

- Please give the results in the units provided.
- Round your results to reasonable precision.
- Exercises do not have to be submitted for correction.
- Solutions of the exercises will be made available on October 4.
- If you have questions, please write an e-mail to: kathrin.volkart@psi.ch

## 1 Electricity generation costs

After the Fukushima disaster in 2011, the Swiss federal government decided to phase-out nuclear energy. In that year, nuclear energy contributed about 41% to the Swiss domestic electricity generation. Expecting constant or increasing electricity demands for the future, the nuclear generation capacity has to be (more than) compensated by non-nuclear generation. Two options for domestic electricity production are natural gas-fired and geothermal power plants. Table 1 shows the techno-economic characteristics of a natural gas-fired combined cycle and a geothermal power plant.

### 1.1 Annuity factor

Calculate the annuity factor *acc* for the two types of power plants. Assume a reasonable interest rate and comment on your selection.

Table 1: Technical characteristics of
the natural gas and geothermal power plants

| | Natural gas | Geothermal |
|---|---|---|
| Power plant efficiency $\eta_e$ | 62% | 11% |
| Life time $n$ | 30 yr | 25 yr |
| Full load hours *load* | 7500 h/yr | 8000 h/yr |
| Investment costs $I$ | 950 CHF/kW$_e$ | 35000 CHF/kW |
| Levelised O&M costs $OM$ | 8.4 Rp./kWh$_e$ | 4.1 Rp./kWh$_e$ |
| Natural gas price $P$ | 10 CHF/GJ$_{th}$ | - |

**Solution:**

Currently, the long-term interest rates relevant for renewable energy projects are very low, for example 2% (https://www.cepweb.org/low-interest-rates-an-opportunity-for-renewables/).

$$acc_{naturalgas} = \frac{i}{1-(1+i)^{-n}} = \frac{0.02}{1-(1+0.02)^{-30}} = \mathbf{0.045\frac{1}{yr}}$$

$$acc_{geothermal} = \frac{i}{1-(1+i)^{-n}} = \frac{0.02}{1-(1+0.02)^{-25}} = \mathbf{0.051\frac{1}{yr}}$$

## 1.2 Generation cost calculations

Calculate the electricity generation costs $G$ of both types of power plants [Rp./kWh$_e$]. Which technology has higher generation costs? *Be careful with the units!*

**Solution:**

$$G = INV + OM + FUEL$$

$$G_{naturalgas} = 100\frac{Rp.}{CHF} * \frac{acc}{load} * I + OM + 0.36 * \frac{Rp.*GJ_{th}}{CHF*kWh_e} * \frac{P}{\eta_e}$$

$$= 100\frac{Rp.}{CHF} * \frac{0.045}{7500} * 950 + 8.4 + 0.36 * \frac{Rp.*GJ_{th}}{CHF*kWh_e} * \frac{10}{0.62}$$

$$= 0.57 + 8.4 + 5.81 = \mathbf{14.8\frac{Rp.}{kWh_e}}$$

$$G_{geothermal} = 100\frac{Rp.}{CHF} * \frac{acc}{load} * I + OM + 0.36 * \frac{Rp.*GJ_{th}}{CHF*kWh_e} * \frac{P}{\eta_e}$$

$$= 100\frac{Rp.}{CHF} * \frac{0.051}{8000} * 35000 + 4.1 + 0.36 * \frac{Rp.*GJ_{th}}{CHF*kWh_e} * \frac{0}{0.11}$$

$$= 22.4 + 4.1 + 0 = \mathbf{26.5\frac{Rp.}{kWh_e}}$$

The power generation costs of the geothermal power plant are about 2 times as high as the ones of the natural gas power plant.

## 1.3 $CO_2$ tax

Switzerland has a $CO_2$ law with stringent domestic emission reduction targets. Natural gas-fired power plants emit significant amounts of $CO_2$ (300-400 g $CO_2$ /kWh$_e$). $CO_2$ taxes are a policy measure which incentivises low-$CO_2$ electricity generation.

Would a $CO_2$ tax of 10 CHF/$GJ_{th}$ on natural gas make geothermal power generation cost-competitive with natural gas power generation?

**Solution:**

$G_{naturalgaswithtax} = 100\frac{Rp.}{CHF} * \frac{acc}{load} * I + OM + 0.36 * \frac{Rp.*GJ_{th}}{CHF*kWh_e} * \frac{P+tax}{\eta_e}$

$= 100\frac{Rp.}{CHF} * \frac{0.045}{7500} * 950 + 8.4 + 0.36 * \frac{Rp.*GJ_{th}}{CHF*kWh_e} * \frac{10+10}{0.62}$

$= 0.57 + 8.4 + 11.6 = \mathbf{20.6\frac{Rp.}{kWh_e}}$

Even with a $CO_2$ tax of $10CHF/GJ_{th}$ the natural gas power plants produce at lower cost then geothermal power plants.

## 1.4 Investment subsidies

Another option to incentivise investments in low-carbon power generation are subsidies on the investment costs. What investment subsidy (CHF/kW) would be required to make geothermal power generation cost-competitive with natural gas power generation?

**Solution:**

$G_{naturalgas} \equiv G_{geothermal,incentive} = 100\frac{Rp.}{CHF} * \frac{acc}{load} * I_{incentive} + OM$

$G_{naturalgas} - OM = 100\frac{Rp.}{CHF} * \frac{acc}{load} * I_{incentive}$

$\frac{G_{naturalgas} - OM}{100\frac{Rp.}{CHF} * \frac{acc}{load}} = I_{incentive}$

$I_{incentive} = \frac{14.8-4.1}{100\frac{Rp.}{CHF} * \frac{0.051}{8000}}$

$I_{incentive} = 16784CHF/kW_e$

An investment subsidy of $35000 - 16784 = \mathbf{18216CHF/kW_e}$ would be required for the geothermal power plant to become cost-competitive with the natural gas power plant.

## 1.5 Broader view

Natural gas power plants emit significant amounts of $CO_2$ and geothermal power plants have relatively high generation costs (see above). Can you think of other weaknesses of these technologies which could hinder their deployment in Switzerland? Think from a broader sustainability perspective, i.e. consider societal, technical, environmental and security of supply aspects.

**Solution:**

Weaknesses of natural gas power generation:

- Air pollutant emissions lead to human health and ecosystem damages.
- Methane leakages from natural gas transport contribute to global warming.
- Security of supply is in question as the fuel has to be imported to Switzerland.
- ...

Weaknesses of geothermal power generation:

- Geothermal power generation is not proven in Switzerland.
- There is the risk of induced seismicity, i.e the drilling can cause earthquakes.
- Materials, particularly chemical substances and solutions, used in the drilling procedure bear the risk of enviromental damages.
- ...

# 2 Technology learning

New technologies are subject to so-called technology learning. With increasing capacity installed, the specific technology cost fall due to the gain in experience. The learning curve is an empirical function that relates total specific investment cost of technologies to their cumulative installed capacity.

## 2.1 Learning curves

Draw the following two lines in Figure 1 below and label them accordingly:

- Learning curve
- Floor cost curve

**Solution:**
$\Rightarrow see Figure 1.$

## 2.2 Learning index

Wind power is another option to expand domestic renewable electricity generation in Switzerland. Up to 2035, the technology is expected to become more competitive compared to conventional natural gas power plants as the currently immature technology undergoes so-called technology learning.

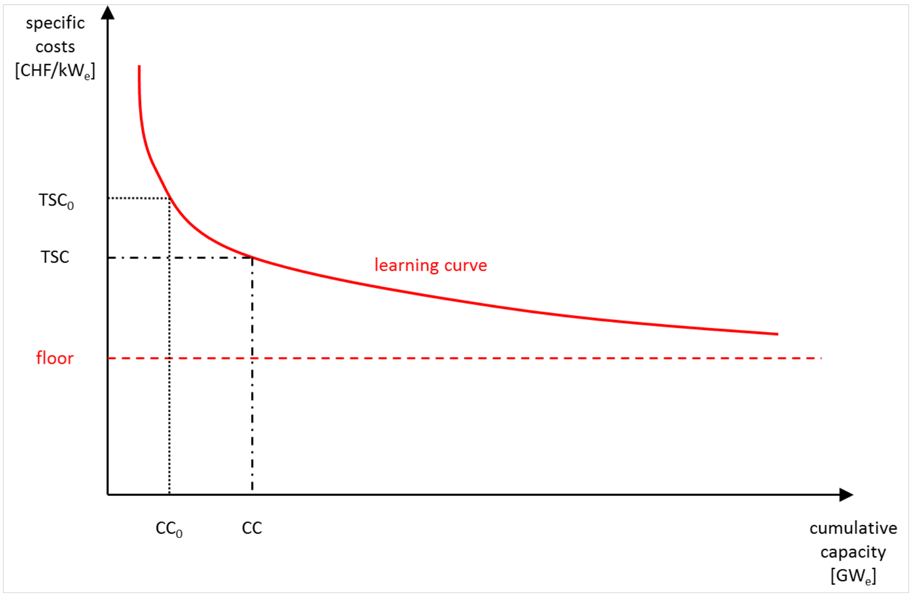


Figure 1: Learning curve

Calculate the learning index $b$ of wind energy [-]. Assume the learning rate $lr$ as stated in the lecture notes [1].

**Solution:**

$lr = 1 - 2^{-b} \Rightarrow b = \frac{-ln(1-lr)}{ln(2)} = \frac{-ln(1-0.15)}{ln(2)} = \mathbf{0.234}$

### 2.3 Technology learning calculations

Calculate the cumulative capacity $CC$ [MW$_e$] of wind power that is required to achieve total specific costs $TSC$ of 1500 CHF/kW$_e$ in 2035. Assume that 1000 CHF/kW$_e$ of the 2100 CHF/kW$_e$ investment costs $TSC_0$ in 2010 are the floor cost *floor*, whereas the rest of the investment cost $SC_0$ undergoes technology learning. The installed wind capacity $CC_0$ in 2010 was 18 MW$_e$.

**Solution:**

$TSC_0 = SC_0 + floor$

$TSC = SC_0 * (\frac{CC}{CC_0})^{-b} + floor$

$\Rightarrow (\frac{CC}{CC_0})^{-b} = \frac{TSC-floor}{SC_0}$

$\Rightarrow CC \approx \mathbf{520MW_e}$

[1] A learning rate of 20% implies that with the doubling of the cumulative capacity, the costs are reduced to 80% of their initial value.

## 2.4 Limitations of the approach

Which considerations have been omitted in the way previous question was formulated? Give arguments and propose a more realistic formulation for the technology learning for wind power.

**Solution:**

Switzerland is not an isolated market. Wind turbines are not developed for and in Switzerland, but for the world market. Hence the initial installed capacity in Switzerland is not relevant. Special to Switzerland are the low wind speeds and the difficult terrain. Therefore, it would be appropriate to consider the ensemble of countries with similar conditions, both for the initial and final capacities.

The specific learning would then be applied to the cost contribution for *difficult conditions*, whereas the remainder (*typical conditions*) is dictated by the world market and its growth. Hence, this would result in a different splitting between floor costs, costs subjected to *global learning*, and costs subjected to *low-wind learning*.