Assignment week 2: Technological learning[1]

Teachers
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Subjects and objectives of this assignment

- Setting up experience curve and calculating progress ratios
- Critically analysing and comparing experience curves for wind turbines and PV-modules (solar cells)
- Calculating uncertainties

Group size
2 persons per group

Background literature (on Moodle)

1. OECD/IEA, Experience curves for energy technology policy (chapters 1, 2 & 3), Organisation for economic co-operation and Development/ International Energy Agency, Paris, 2000.

Further Reading

2. Junginger, M., & Louwen, A. (Eds.). (2020). Technological Learning in the Transition to a Low-Carbon Energy System: Conceptual Issues, Empirical Findings, and Use, in Energy Modeling. Academic Press.
3. Weiss, M.; Patel, M.; Junginger, M.; Blok, K.: Analyzing price and efficiency dynamics of large appliances with the experience curve approach. Energy Policy, vol. 38, pp. 770–783. 2010
4. Weiss M.; Patel M. K.; Junginger M.; Perujo A.; Bonnel P.; van Grootveld G.: On the electrification of road transport - Learning rates and price forecasts for hybrid-electric and battery-electric vehicles. Energy Policy 48 (2012) pp. 374–393, 2012

Submission date
The report has to be uploaded on Moodle on Wednesday 6 March 2024 **at 17:00 at the latest**. Any submissions later than this date will not be reviewed. Only a single (MS-Word or pdf) file will be accepted.

Debriefing
The debriefing of the assignment will take place on Friday 8 March 2024 at 8:15.

Exercise 1. Experience curves and uncertainty (12p)
From 2003 until 2020 the cumulative installed capacity of wind farms in Northern Europe increased from 87 to 2235 MW. Every year, price lists of ten different manufacturers were collected and listed in Table 1.

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[1] Courtesy Utrecht University; apart from minor modifications this assignment has been taken over from the course "Advanced Energy Analysis" of the Copernicus Institute of Sustainable Development at Utrecht University, Netherlands.

<u>Question 1a</u> (8p)
Prepare an experience curve making use of the data given in Table 1, plotting the mean price per kW against the cumulative installed capacity. Correct for inflation using the year 2020 as currency base year. Make two graphs, one with axes using linear scales, and one using logarithmic scales. Report corrected prices, curve equations and coefficient of determination (R^2) values for the fit in your report.[2] Pay attention that you present these graphs in an orderly fashion.

Next, calculate the progress ratio, the total number of doublings of the installed capacity in the Northern Europe from 2003-2020, and the average growth percentage with which the capacity in Northern Europe has increased annually.

Hint: To calculate the *Progress Ratio*, you need to know the *Learning index* b. To determine the value of b, you can let Excel calculate the trendline for the Option "Power".

Table 1 Development of the cumulative installed capacity and published investment prices of wind farms in Northern Europe 2003-2020

		Price given by different manufacturers (€/kW)								
Year	Cumulative capacity (MW)	A	B	C	D	E	F	G	H	Consumer Price-Index (CPI) (2003=100)
2003	87	1500	1000	2015	985	1415	1095	985	1300	100.0
2004	105	1290	995	1805	985	1300	1015	905	1190	103.9
2005	132	1195	940	1590	955	1085	985	890	1135	107.7
2006	151	1120	910	1580	915	1095	965	915	1085	110.0
2007	225	1000	870	1515	875	1070	940	885	1000	113.0
2008	295	1025	845	1515	855	1040	945	900	1035	115.2
2009	325	1015	860	1530	840	1015	960	905	1010	117.7
2010	360	1020	845	1475	850	1020	950	885	1020	120.2
2011	408	1025	840	1455	860	990	960	915	1015	122.6
2012	458	1005	840	1405	825	970	945	890	1025	125.3
2013	480	1005	855	1355	840	950	930	880	1000	128.6
2014	681	975	820	1305	820	930	940	870	1000	134.4
2015	910	955	820	1280	825	910	935	875	955	139.0
2016	1082	955	830	1215	830	915	910	845	955	141.9
2017	1223	930	815	1140	820	880	910	825	935	143.6
2018	1559	910	805	1050	815	850	900	815	930	146.0
2019	1747	890	805	990	810	855	885	820	935	148.7
2020	2235	875	805	950	805	820	865	800	925	151.6

[2] Check the appendix *Coefficient of determination* for information on fitting curves on data

Question 1b (4p)
You have already prepared the experience curve in the previous question. Please display the standard uncertainty, also referred to as "standard error of the mean" (SEM), of the mean price for each year on the same plot with the help of error bars. Comment on your results.

Hints: The standard error of the mean (SEM; also referred to as "Standard uncertainty of the mean" and as "Standard deviation of the mean)" measures the accuracy of the sample. The SEM is always smaller than the standard deviation (SD) as the latter measures the spread of the whole dataset. The SEM is calculated by dividing the standard deviation by the square root of the sample size (see appendix on statistical indicators).

Exercise 2. (10p)
For the same time period the installed global capacity of onshore wind farms (including Northern Europe) is given in Table 2.

Table 2 Growth of the global cumulative installed capacity

Year	Cumulative capacity (MW)
2003	1970
2004	2632
2005	2817
2006	3577
2007	4434
2008	5438
2009	6818
2010	9086
2011	12587

Year	Cumulative capacity (MW)
2012	15579
2013	22003
2014	29065
2015	37235
2016	43799
2017	51048
2018	59204
2019	67687
2020	75609

Question 2a (8p)
Make two experience curve graphs again, one with linear scale-axes and one with logarithmic axes. Next, calculate the progress ratio, the total number of doublings of the installed global capacity from 2003-2020, and the average growth percentage by which the global capacity has increased annually. Assume that the prices from Exercise 1 also reflect global price levels.

Question 2b (2p)
As you have noticed, there is a difference in the progress ratios of Exercise 1 and 2. What is the reason for the difference in the progress ratios in this specific case?

Exercise 3. Geographic differences in learning curves and knowledge spillovers (8)

Read the abstract and discussion section (pages 13,14) of the following article: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/02/A-critical-assessment-of-learning-curves-for-solar-and-wind-power-technologies-EL-43.pdf

Question 3a (4p)
What factors can cause differences between local and worldwide learning curves for renewable energy?

Question 3b (4p)
The same article suggests that one assumption underlying learning curves is the common occurrence of knowledge spillovers (or learning spillovers) between countries. Knowledge spillover is a transfer of knowledge without full compensation or significant effort (i.e., nearly 'automatic'). What are arguments for and against the existence knowledge spillovers between countries, and what impact does it have on learning curves?

Exercise 4. Use of experience curves to estimate future technology performance (30p)

Some years ago, the Swiss government wanted to stimulate the development of solar modules. Their target was to install 0.2% of the globally produced PV-modules on the roofs of Swiss households. They were aware of the fact that solar electricity was still too expensive to compete with conventional power generation, but they expected that the price would continue to decline in the subsequent years. In order to stimulate the installation of solar modules, they wanted to subsidise the share of the investment costs that makes the investment economically unattractive when compared to conventional power generation.

The Swiss government wanted to know when they could expect that the cost of electricity from solar cells would break even with the cost of conventional power generation. They were interested in how much money would be needed to subsidize solar cells up to this point.

Question 4a (10p)
Provide an answer in which year you expect costs of electricity from solar cells to break even with conventional power generation. To do so, please use the template.
Projections of technological progress are subject to uncertainty. Therefore please answer these two questions for three PR values, i.e. 63%, 75% and 86%.

Hints: Use the data from Table 3 (below). You will need to extrapolate experience curves into the future. You can assume that every year exactly 0.2% of the globally annually added capacity is installed in Switzerland.[3] Explicitly report your assumptions, the equations you use and your results. Provide graphs of your results where appropriate.

[3] See slide 60 from this week 3 for using growth rates in calculations

Table 3: Assumed data on the economics of PV panels in the Switzerland

Break-even price for a PV-system	CHF1775 / kW_p
Required roof surface	About 7.5 m^2 / kW_p
Growth expectations of the cumulative global PV capacity	20% / year
Optimistic PR (PR_{opt})	63%
Medium PR (PR_{med})	75%
Pessimistic PR (PR_{pess})	86%
Investment costs for PV systems at the beginning of 2012	CHF4200 / kW_p (includes module costs as well as inverter, cables, support structure and installation costs)
Cumulative installed global capacity at the beginning of 2012	100,000 MW_p
Cumulative installed capacity in Switzerland at the beginning of 2012	200 MW_p

Question 4b (5p)
Estimate how much roof space of each house is needed for PV-panels when the break-even point is reached. Analyse if this value is a problem. In order to do so, make an educated guess (keep it simple!) on how much roof area is available per household (assume 3.58 million households in Switzerland). State all your assumptions and references where needed.

Question 4c (10p)
Calculate the total investment costs for the PV systems that will be installed in Switzerland until the break-even point is reached for each of the PR scenario assumed in Question 4a.[4]

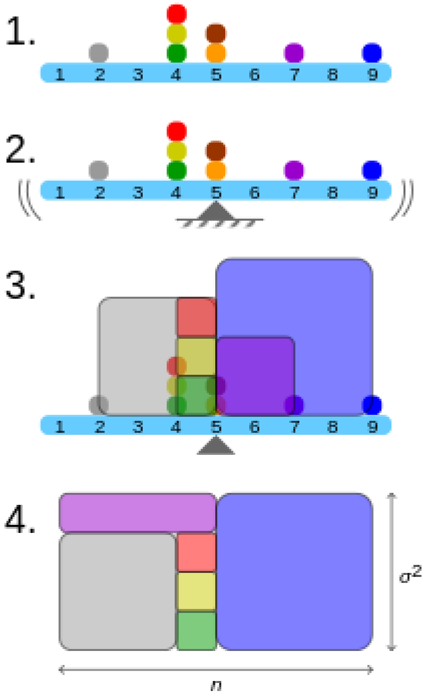
Question 4d (5p)
Assuming that the Swiss government will pay the non-profitable part of the PV-systems, and the costs of conventional power generation remains constant, what will be the costs for the Swiss government?

[4] Hint: See appendix *Common integrals* for integral solutions of common functions

Appendix: Statistical indicators – Basics

Variance

French: Variance



Geometric visualisation of the variance of the example distribution:

- A frequency distribution is constructed.
- The centroid of the distribution gives its mean.
- A square with sides equal to the difference of each value from the mean is formed for each value.
- Arranging the squares into a rectangle with one side equal to the number of values, n, results in the other side being the distribution's variance, σ^2.

Wikipedia, 2016

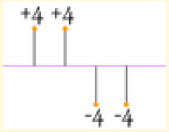
Equations:

- Variance (Sample Variance) $$s^2 = \frac{\sum_{i=1}^{n}(X_i - X_{avg})^2}{n-1}$$

http://www.macroption.com/population-sample-variance-standard-deviation/

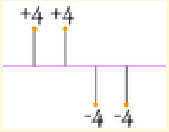
Note: The standard deviation is the square root of the variance:

If we just added up the differences from the mean ... the negatives would cancel the positives:



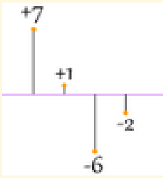
$$\frac{4 + 4 - 4 - 4}{4} = 0$$

So that won't work. How about we use absolute values ?



$$\frac{|4| + |4| + |-4| + |-4|}{4} = \frac{4 + 4 + 4 + 4}{4} = 4$$

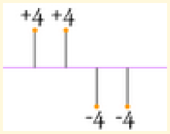
That looks good (and is the Mean Deviation), but what about this case:



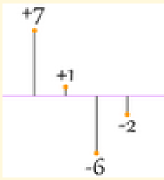
$$\frac{|7| + |1| + |-6| + |-2|}{4} = \frac{7 + 1 + 6 + 2}{4} = 4$$

Oh No! It also gives a value of 4, Even though the differences are more spread out!

So let us try squaring each difference (and taking the square root at the end):



$$\sqrt{\frac{4^2 + 4^2 + 4^2 + 4^2}{4}} = \sqrt{\frac{64}{4}} = 4$$



$$\sqrt{\frac{7^2 + 1^2 + 6^2 + 2^2}{4}} = \sqrt{\frac{90}{4}} = 4.74...$$

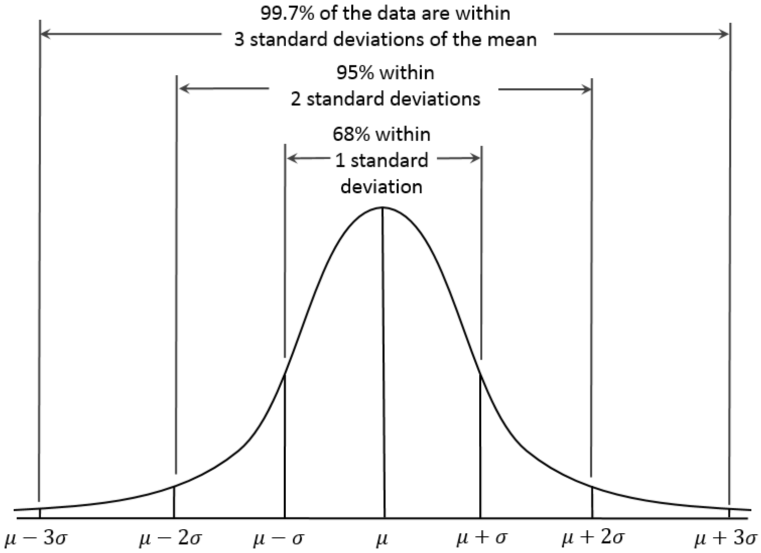
That is nice! The Standard Deviation is bigger when the differences are more spread out ... just what we want!

In fact this method is a similar idea to distance between points , just applied in a different way.

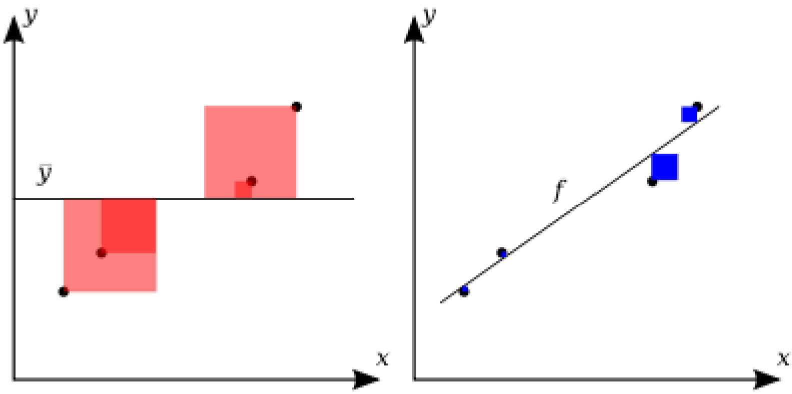
And it is easier to use algebra on squares and square roots than absolute values, which makes the standard deviation easy to use in other areas of mathematics.

http://www.mathsisfun.com/data/standard-deviation.html

Below we look more carefully into what the standard deviation means.

Standard Deviation *French: Écart type*	The standard deviation (SD, also represented by the Greek letter sigma σ or s) is a measure that is used to quantify the amount of variation or dispersion of a set of data values. The graph below shows the percentage of values that lie within a band around the mean in a normal distribution with a width of one, two and three standard deviations (68%, 95% and 99.7% respectively).  Wikipedia, 2016 Equations: • **Standard** Deviation (Sample Standard Deviation) $s = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_{avg})^2}{n-1}}$ http://www.macroption.com/population-sample-variance-standard-deviation/
Practical hint	In Excel, variance and standard deviation can be easily calculated using the built-in functions: VAR.S, and STDEV.S or STDEV (of course you can also calculate them directly using the formulas above if you like). http://www.macroption.com/population-sample-variance-standard-deviation/

Standard error of the mean (SEM) **= Standard uncertainty of the mean** **= Standard deviation of the mean** *French: Erreur type de la moyenne*	Standard error is a way to quantify the accuracy of a sample or the accuracy of multiple samples by analyzing deviation among the means. As the size of the sample data grows larger, the standard error of the mean decreases versus the standard deviation. $\mathrm{SE}_{\bar{x}} = \frac{s}{\sqrt{n}}$ where s is the Standard deviation and n is the size (number of observations) of the sample.
Practical hint	In Excel, there is no function to automatically calculate the standard error of the mean but it is easily calculated once the standard deviation and the number of observations are known.

Coefficient of determination *French: Coefficient de détermination*	The coefficient of determination, denoted R^2 and pronounced R squared, is a number that indicates how well data fit a statistical model – sometimes simply a line or a curve. An R^2 of 1 indicates that the regression line perfectly fits the data, while an R^2 of 0 indicates that the line does not fit the data at all.  $$R^2 = 1 - \frac{SS_{\text{res}}}{SS_{\text{tot}}}$$ A data set has n values marked $y_1...y_n$ (collectively known as y_i or as a vector $y = [y_1...y_n]^n$), each associated with a predicted (or modelled) value $f_1...f_n$ (known as f_i, or sometimes $\hat{y}_i$, as a vector f). Define the residuals as $e_i = y_i - f_i$ (forming a vector e). If $\bar{y}$ is the mean of the observed data: $$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$ then the variability of the data set can be measured using three sums of squares formulas: • The total sum of squares (proportional to the variance of the data): $$SS_{\text{tot}} = \sum_i (y_i - \bar{y})^2,$$ • The sum of squares of residuals, also called the residual sum of squares: $$SS_{\text{res}} = \sum_i (y_i - f_i)^2 = \sum_i e_i^2$$

	• The most general definition of the coefficient of determination is $R^2 \equiv 1 - \frac{SS_{\rm res}}{SS_{\rm tot}}.$ Wikipedia, 2016
Practical hint	In Excel, plot your data points in a graph. Select/mark these data points and press the right mouse button which will offer “Add Trendline” as one of the options. You may then choose the trendline options (e.g., linear, exponential etc.). Checking the boxes “Display Equation on chart” and “Display R-squared value on chart” provides you with the full information

Common integrals

1. $\int k\,dx = kx + C$ Integral of a constant k is kx + C
2. $\int dx = x + C$ Special case of the above where k = 1
3. $\int x^n\,dx = \frac{x^{n+1}}{n+1} + C$, where $n \neq -1$
4. $\int \frac{1}{x}\,dx = \ln|x| + C$
5. $\int \sin x\,dx = -\cos x + C$
6. $\int \sin ax\,dx = -\frac{1}{a}\cos ax + C$
7. $\int \cos ax\,dx = \frac{1}{a}\sin ax + C$
8. $\int \cos x\,dx = \sin x + C$
9. $\int \sec^2 x\,dx = \tan x + C$
10. $\int \csc^2 x\,dx = -\cot x + C$
11. $\int \sec x \tan x\,dx = \sec x + C$
12. $\int \csc x \cot x\,dx = -\csc x + C$
13. $\int \frac{1}{\sqrt{1-x^2}}\,dx = \sin^{-1} x + C$
14. $\int \frac{1}{\sqrt{1-x^2}}\,dx = -\cos^{-1} x + C$
15. $\int \frac{1}{1+x^2}\,dx = \tan^{-1} x + C$
16. $\int \frac{1}{1+x^2}\,dx = -\cot^{-1} x + C$
17. $\int \frac{1}{x\sqrt{x^2-1}}\,dx = \sec^{-1} x + C$
18. $\int \frac{1}{x\sqrt{x^2-1}}\,dx = -\csc^{-1} x + C$
19. $\int e^x\,dx = e^x + C$
20. $\int a^x\,dx = \frac{a^x}{\log a} + C$