**Report template - All instructions can be found in the Jupyter Notebook.**

## Methods for technical and economic energy analysis, week 9

# Linear Optimization for Energy System Modeling

**Teachers**

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Please include all plots, discussions, and results into this report (unless instructions say otherwise).

Use the boxes in this document for your answers (text and plots).

**The number of words mentioned for the discussion parts is just an information on how long the answer in the solution is. This can serve as a guideline. Of course you can write longer or shorter answers.**

# Access Instructions

The online teaching environment can be found at:

<https://129.194.172.8/jupyter/>

Please use the same login procedure and user name/password as for the Monte Carlo assignment.

# Submission deadline

This report, the Excel analysis file, and the Jupyter notebook (\*.ipynb) must be uploaded to Moodle by Wednesday 13 May 2020 at 17:00 at the latest. Any submission later than this date will not be reviewed.

# Exercise 1: Understanding the objective function.

#### Task 1.a (Discussion), **5 points**: Based on the code above, your own reasoning, and the discussion in the lecture, explain the total cost in detail: What are the units of each factor and term? How do they add up to yield a total cost? Explain in words. What is the unit of the total cost? What role does the efficiency (eff) play? (100 words)

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# Exercise 2: Inspection of the input data.

#### Task 2.a (Analysis/Discussion), **4 points**: Calculate the total variable cost (fuels and emissions) per produced MWh for each of the power plants (units EUR/MWhelectricity), i.e. how much does it cost to produce one MWh of electricity using each of the plants? Report the values and describe your reasoning in words (50 words).

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#### Task 2.b (Analysis/Discussion), **4 points**: Calculate the levelized cost of new wind and solar plants per produced MWh. Report the values and describe your reasoning in words. (50 words)

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#### Task 2.c (Analysis/Discussion), **7 points**: Which price on CO2 emissions would be necessary to make new wind and solar plants competitive with the existing coal plants, only considering levelized costs of the former and total variable costs of the latter? Report the values and describe your reasoning in words. Hint: Competitiveness means that the levelized costs are equal. Important: Find the equation to calculate this, don't just try different values. (80 words)

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#### Task 2.d (Analysis/Discussion), **8 points**: Which price on CO2 emissions would be necessary to make new gas power plants competitive with respect to coal power plants and old gas power plants? Assume that the new gas plants produce electricity at full power all year round. What changes if they only produce power during 1, 2, or 3 seasons? Report all values for 1-4 seasons. In your own words, describe what it means that the competitiveness of the new plants depends on the number of seasons during which they produce power. Hint: The total cost of the new gas plants consists of fuel, CO2 prices, and the investment cost; use the same approach as in Task 2.c. (200words)

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#### Task 2.e (Analysis/Discussion), **4 points**: Plot the capacity factors of the new wind and new solar plants. What do you notice when comparing the two curves qualitatively? (20 words) Calculate the yearly capacity factor of both new wind and new solar from the seasonal capacity factors provided to you. How can you calculate the capacity factor in the more general case where not all seasons have the same length? Describe your reasoning in words. Hint: Remember how the capacity factor was defined in the lecture. (80 words)

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| <insert plot here> |
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# Exercise 3: Adding the additional constraints.

#### Task 3.a (Discussion), **6 points**: Reflect on which additional constraints are required for the model formulation. Report the two additional constraints and explain the reasoning: Why is the constraint needed? What does it enforce (in your words)? (0 points without explanation). (120 words with the constraints)

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| <insert discussion here> |

#### BONUS Task 3.b (Code), **5 points**: Add the two additional constraints to the model, in the same way as the supply\_constraint above. Please copy the code to the report. This is a bonus task. If you want to skip it, please ask for the code in order to proceed with the assignment. (120 words with the constraints)

<in Jupyter Notebook>

# Exercise 4: Analyzing the model results.

#### Task 4.a (Analysis), **2 points**: Draw a stacked bar plot which shows the average produced power for each season and each power plant (one plot, four bars (seasons), stacked by power plant).

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| <insert plot here> |
| Task 4.a: Power production for each season. |

#### Task 4.b (Analysis), 2 points: Calculate the total yearly capacity factor of all plants and draw them as a bar plot (one bar for each plant).

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| <insert plot here> |
| Task 4.b: Capacity factors for all power plants. |

#### Task 4.c (Discussion), 4 points: Compare the capacity factors of the nuclear, hard coal and gas plants to the respective variable costs of these plants (task 2.a). Given the calculated costs, explain why some plants have higher capacity factors than others. (70 words)

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#### Task 4.d (Discussion), 4 points: Are any new wind, solar, or gas plants added to the system? Explain why or why not for each of the three plants. Take into account the results from task 2.c and 2.d. Which price on CO2 emissions would be required to make them competitive? How does the price assumed in the model compare to this? (Note: If you don't remember the CO2 price currently used by the model, you can either scroll back up, or execute m.price\_co2.display() in a new cell) (90 words)

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| <insert discussion here> |

# Exercise 5: Comparison of the 14 and 15 EUR/tCO2 model runs

#### Task 5.a (Analysis), **3 points**: Compare the results (produced average power from all plants) of the models in 2 stacked bar plots (two plots, four bars (seasons) in each plot, stacked by power plant).

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| <insert plot here> | <insert plot here> |
| Figure Task 5.a: Produced power for each season in the two considered CO2 emission price cases. | |

#### Task 5.b (Discussion), **5 points**: What are the differences in terms of power production between the cases with 14 and 15 EUR/tCO2? Why is it beneficial to avoid production from old gas plants by building new ones? In the 14 EUR/t case, what limits the investment in new gas plants compared to the 15 EUR/t case? Use the results from task 2.d. to answer these questions. (90 words)

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# Exercise 6: Optimal electricity mix for changing CO2 prices.

#### Task 6.a (Analysis), **3 points**: Draw a stacked bar chart of the total produced energy (sum over all seasons) in TWh/yr as a function of the CO2 emission price (Consider: What are the units of the output data? How do you obtain TWh/yr from that?). Tip: Trends are easier to see if you set the bar gap width to 0% (see e.g. https://bit.ly/3ecDAXy).

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| <insert plot here> |
| Figure task 6.a: Optimal electricity mix for increasing CO2 prices. |

#### Task 6.b (Discussion), 4 points: An abrupt transition in the optimal system configuration occurs for a certain CO2 price range, first to much more new gas power, then to much more wind power. Does this transition occur roughly where you would expect it? Explain in words. Take into account the results from exercise 2. (60 words)

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#### Task 6.c (Discussion), 4 points: Once the installation of new wind and solar capacity becomes more beneficial than the installation of new gas plants, it is initially only wind power that's being installed. Why is wind more beneficial than solar power? Take into account the results from exercise 2. (60 words)

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#### Task 6.d (BONUS TASK), **3 points**: Qualitatively, what drives the increasingly important role of solar power starting from a certain CO2 price? Hint: Get back to this question after working on Exercise 8. (60 words)

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# Exercise 7: Electricity/Shadow prices.

#### Task 7.a (Analysis), **2 points**: Plot the electricity prices (EUR/MWh) as a function of the season (line plot). Include all emission prices in the same plot.

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| <insert plot here> |
| Figure Task 7.a: Electricity/Shadow prices by season for different CO2 emission prices. |

#### Task 7.b (Discussion), **5 points**: Discuss the qualitative change of the price profile for increasing power prices. Why do the electricity prices change only rather little for a four-fold increase of emission prices from 20 to 80 EUR/MWh? Compare to the result of task 6.a. What could be the reason for the strongly different 200 EUR/tCO2 profile? Hint: Try to adjust the CO2 prices in task 2.a and compare the levelized costs to the electricity prices. (100 words)

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# Exercise 8: Specific value of wind power forced into the power system

#### Task 8.a (Analysis), **5 points**: Using the shadow price of demand/electricity prices (EUR/MW) from the table printed below and the capacity factors from Exercise 2, calculate the specific revenue of the new wind turbines (revenue per installed capacity, EUR/MW/year, single line plot with markers). Plot the specific wind turbine revenue as a function of the installed new wind capacity. Also plot the shadow prices for the 4 seasons separately (all in the same plot) as a function of the new wind capacity (single bar plot with 11 bar groups, not stacked).

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| <insert plot here> |
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| Figures Task 9.a: Specific wind value and electricity prices for increasing wind capacity. |

#### Task 8.b (Analysis), **2 points**: Plot the total cost (objective function) as a function of the installed wind turbine capacity (line plot, units: billion (1e9) EUR/year).

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| <insert plot here> |
| Figures Task 9.b: Total cost for increasing PV capacity. |

#### Task 8.c (Discussion), **5 points**: Describe the plotted total cost (task 8.b). What is going on here? Does the minimum cost occur where you would expect it? Explain using the results of exercise 6. (60 words)

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#### Task 8.d (Discussion), 5 points: What do you observe in the plotted specific revenue (task 8.a)? Explain what's going on (steps!) by comparing to the plotted electricity prices (task 8.a). What is the specific revenue of wind turbined around the optimum from task 8.b? Compare to the annualized investment cost of wind turbines. Describe your conclusions in your own words. (120 words)

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#### Task 8.e (Discussion), **3 points**: So far we have only considered new wind turbine capacity. What is the specific value (EUR/MW/year) of the old wind turbine plants? Explain your reasoning. (No additional calculations required! Think how the calculation would change if you did it explicitly.). (50 words)

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#### Task 8.f (Discussion), 3 points: What do these results mean in a real power system? Can you think of how this change in specific revenue might be problematic? (60 words)

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# BONUS Exercise 9: Impact of storage on solar power revenue

#### Task 9.a (Discussion), **5 points**: Describe the changes to the original model constraints when including storage (in words). Describe the reasoning behind the additional storage constraint (in words). (100 words)

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#### Task 9.b (Analysis), **3 points**: Plot the charging and discharging power (MW, data printed below) for 60'000 and 140'000 MW of new wind power (one plot, four bars)..

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| <insert plot here> | <insert plot here> |
| Figure Task 10.b: Charging and discharging power by season for two different wind capacities. | |

#### Task 9.c (Analysis), **3 points**: Like in Task 8.a, calculate the specific revenue of wind power (EUR/MW/year) with and without storage and plot the two curves in a single plot (as function of the wind power capacity).

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| <insert plot here> |
| Figure Task 9.c: Specific PV revenue with and without storage. |

#### Task 9.d (Analysis), **3 points**: Plot the electricity prices as a function of the season for 60'000 MW of PV capacity with and without storage (two plot series in one plot). Make another identical plot for 140'000 MW PV capacity.

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| <insert plot here> | <insert plot here> |
| Figures Task 9.d: Electricity prices with and without storage by season; left: 140’000 MW wind capacity; right: 200'000 MW wind capacity | |
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#### Task 9.e (Discussion), **8 points**: Is the wind power revenue larger or smaller if there is storage in the system? Why? Explain by starting from the impact of wind power on prices, then the impact of storage on prices, then the impact of prices on wind power revenue. Base your discussion on plot 9.c and the plot of the wind power capacity factors from task 1.e. What do you think happens at the highest wind power capacity? (150 word)

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| <insert discussion here> |