**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)*

<insert here>

- Fuel costs have units EUR/MWh_fuel; dividing this by efficiency yields EUR/MWh_el. CO2 price (EUR/t) times CO2 intensity (t/MWh_fuel) has the same units as fuel costs, same conversion to EUR/MWh_el using the efficiency. Power (MW) times season_weight (hours/year) is energy per year (MWh_el/year). Multiplied with the specific cost per unit of produced electricity (EUR/MWh_el) gives EUR/year, which is also the unit of the total cost. The total fixed costs are given by the specific fixed cost EUR/MW/year for newly installed capacity times the new capacity (MW). This is again EUR/year.
- In this simple picture, the efficiency is the conversion factor of fuel energy to electric energy.

## 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/$MWh_{electricity}$), 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).*

<insert here>

The total variable costs are given by the fuel costs and the CO2 intensity times the CO2 price, divided by the efficiency (just like in the objective function):

(fuel_cost[plant] + co2_intensity[plant] * price_co2) / eff[plant]

For 5EUR/t_CO2 the obtained values (EUR/MWh_electricity) are:

| | |
|---|---|
| coal | 25.5 |
| gas | 74.5 |
| gas_new | 55.9 |
| nuclear | 5.8 |

Zero for all other plants.

*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)*

<insert here>

Since the fixed installation costs are annualized (EUR/MW/year), we can just divide them by the yearly full load hours, i.e. sum(cf * 2190hours/year) with units hours/year: Then the LCOE are 107.2 EUR/MWh (solar) and 99.9 EUR/MWh (wind).

*Task 2.c (Analysis/Discussion), **7 points**: Which price on $CO_2$ 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)*

<insert here>

The variable costs of the coal plants must be equal the levelized wind and solar costs we just calculated. Then we can solve this equation for the CO2 price:

(fuel_cost[coal] + co2_intensity[coal] * price_co2) / eff[coal] = LCOE[wind]
=> price_co2 = (LCOE[wind] * eff[coal] - fuel_cost[coal]) / co2_intensity[coal]

Solar power is competitive with coal power for CO2 emission prices of 100.77 EUR/t or higher; wind power requires CO2 emission prices greater 92.24 EUR/t.

*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)*

<insert here>

Conceptually identically to task 2.c we set the levelized cost of new gas power plants equal the levelized cost of coal power plants (same for old gas plants). In this case we need to include the levelized investment cost of the new gas plants, which depends on the number of seasons the plant is operating (fixed_costs[gas_new]/(2190*n)). Also, new gas plants have variable costs (emissions and fuels), in contrast to the previous case of wind and solar plants.

fixed_costs[gas_new]/(2190*n) + fuel_cost[new_gas]/eff[new_gas] +
co2_intensity[new_gas]*co2_price/eff[new_gas]
= fuel_cost[coal]/eff[coal] + co2_intensity[coal]*co2_price/eff[coal]

….. (solve for price_co2)=>

price_co2 = (fixed_costs[gas_new]/(2190*n) + fuel_cost[new_gas]/eff[new_gas] - fuel_cost[coal]/eff[coal]) / (co2_intensity[coal]/eff[coal] - co2_intensity[new_gas]/eff[new_gas])

…. Analogously for old gas plants (instead of coal).
The minimum CO2 prices to replace old coal and gas plants with new gas plants are reported in the table below:

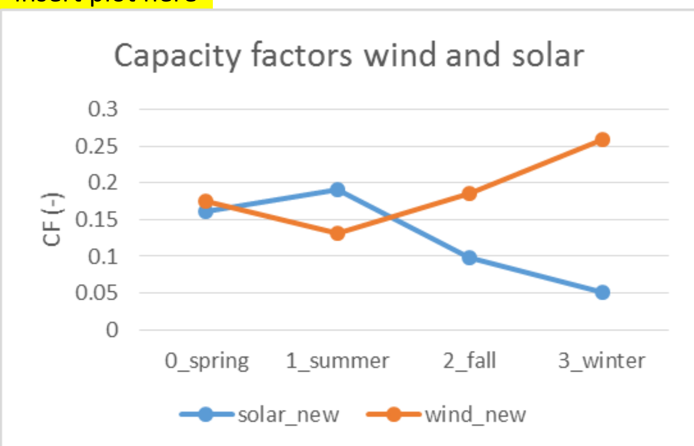
| Operating time (hours/year) | Minimum CO2 price to replace coal | Minimum CO2 price to replace old gas plants |
|---|---|---|
| 2190 | 140.0 | 189.2 |
| 4380 | 101.9 | 14.2 |
| 6570 | 89.2 | -44.2** |
| 8760 | 82.9 | -73.4** |

**Negative prices mean it is beneficial to replace the old gas plants even if the CO2 price is zero.

New plants have lower levelized cost the more electricity they produce during the year, since the investment cost is spread out over a larger number of units of electricity: It is therefore easier to justify their installation if they replace old plants during more seasons.

*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)*

<insert plot here>




<insert discussion here>

Observation: The wind and solar resources are somewhat complementary: High PV power production correlates with low wind power production and vice versa.

Total capacity factor: The total energy produced by a single unit of capacity (MWh/year) follows directly from the sum of the seasonal capacity factors times 2190 MWh/year, the energy a single unit of capacity would produce during a season if it were to operate at constant full output power. The total capacity factor follows by dividing this total energy (MWh/yr) by the yearly energy produced from a single unit of capacity operating at full output power: 8760 MWh/yr. So: sum(cf) * 2190/8760 =

| | |
|---|---|
| solar_new | 12.5% |
| wind_new | 18.8% |

In case the seasons have different durations, this can be generalized to (cf1*season_weight1 + cf2*season_weight2 + ...)/8760

## 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)*

<insert discussion here>

- Capacity constraint: For each power plant and each season, the produced power must be equal or less the installed power capacity. Without this constraint, the availability of low-cost nuclear power would be unlimited. In case of power plants with the possibility to add new capacity, the total capacity consists of the added old and new capacities.

```
def capacity_constraint_equation(m, plant, season):
    if plant in m.new_power_plants:
        return m.pwr[plant, season] <= m.capacity_old[plant] + m.cap_new[plant]
    else:
        return m.pwr[plant, season] <= m.capacity_old[plant]

m.capacity_constraint = po.Constraint(m.power_plants * m.seasons,
rule=capacity_constraint_equation)
```

- Capacity factor constraint: For each wind and solar plant and each season, the produced power must be equal the installed capacity times the capacity factor. Without this constraint the renewable plants could produce power at full nominal power all year round. In case of power plants with the possibility to add new capacity, the total capacity consists of the added old and new capacities.

```
def cf_constraint_equation(m, plant, season):
    if plant in m.new_power_plants:
        return m.pwr[plant, season] == m.cf[plant, season] * (m.capacity_old[plant] +
m.cap_new[plant])
    else:
        return m.pwr[plant, season] == m.cf[plant, season] * (m.capacity_old[plant])

m.cf_constraint = po.Constraint(m.wind_solar, m.seasons, rule=cf_constraint_equation)
```

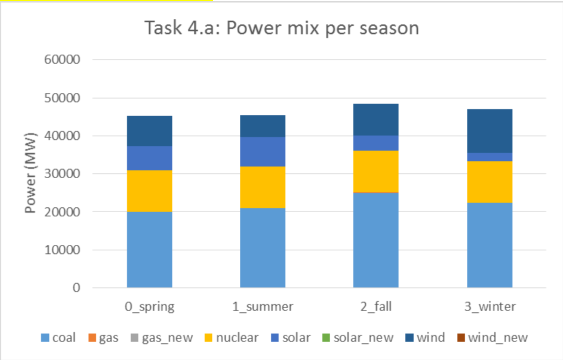
*BONUS Task 3.b (Code), **5 points**: Add the two additional constraints to the model, in the same way as the supply_constraint above. Please copy the code to the report. This is a bonus task. If you want to skip it, please ask for the code in order to proceed with the assignment. (120 words with the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

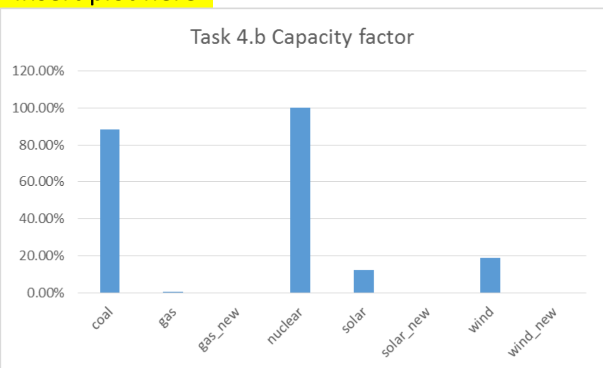
<insert plot here>




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).*

<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)*

<insert discussion here>

Nuclear plants are producing at full output during all seasons. With a total variable cost of 5.8 EUR/MWh they have the lowest running cost by far. Coal power production is limited by the residual load (demand minus wind and solar minus nuclear power). As the second cheapest generator it reaches maximum output only in fall. During this season also the expensive gas power plants produce minor amounts of power.

*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)*

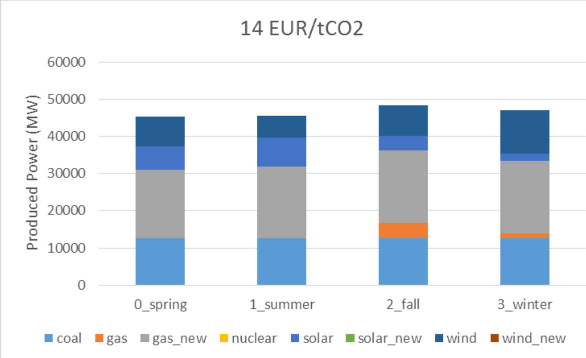
<insert discussion here>

The levelized cost of new gas, wind, and solar power would need to be competitive with the old coal power plants' variable cost. This is only the case for CO2 emission prices greater than 80-100 EUR/t (task 2.c, task 2.d). New gas power plants could replace old gas power plants at this CO2 price, but only if they were able to run during at least three seasons (task 2.d). This is not the case here since the old gas plants operate during a single season only.

# 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).*

<insert plot here>




<insert plot here>

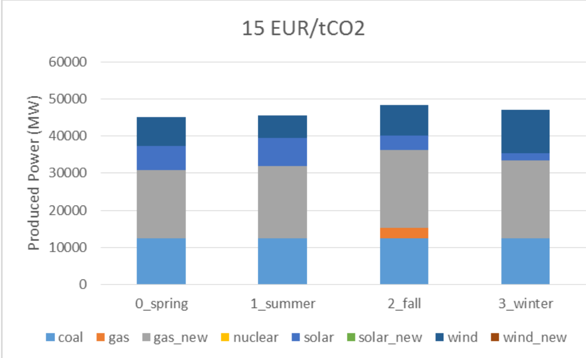



Figure Task 5.a: Produced power for each season in the two considered CO2 emission price cases.

*Task 5.b (Discussion), **5 points**: What are the differences in terms of power production between the cases with 14 and 15 EUR/t$CO_2$? 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)*

<insert discussion here>

Minor amounts of new gas plants are built in the 15 EUR/t case. As shown in task 2.d it pays off to replace old gas plants with new ones even if the new ones are only running for 2 seasons. This is the case for CO2 emission prices of approximately 14.17 EUR/t and higher. In the 14 EUR/t case the CO2 price is not high enough to justify this additional investment: It would only be economically beneficial if the new plants could run during at least 3 seasons.

## 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).*

<insert plot here>

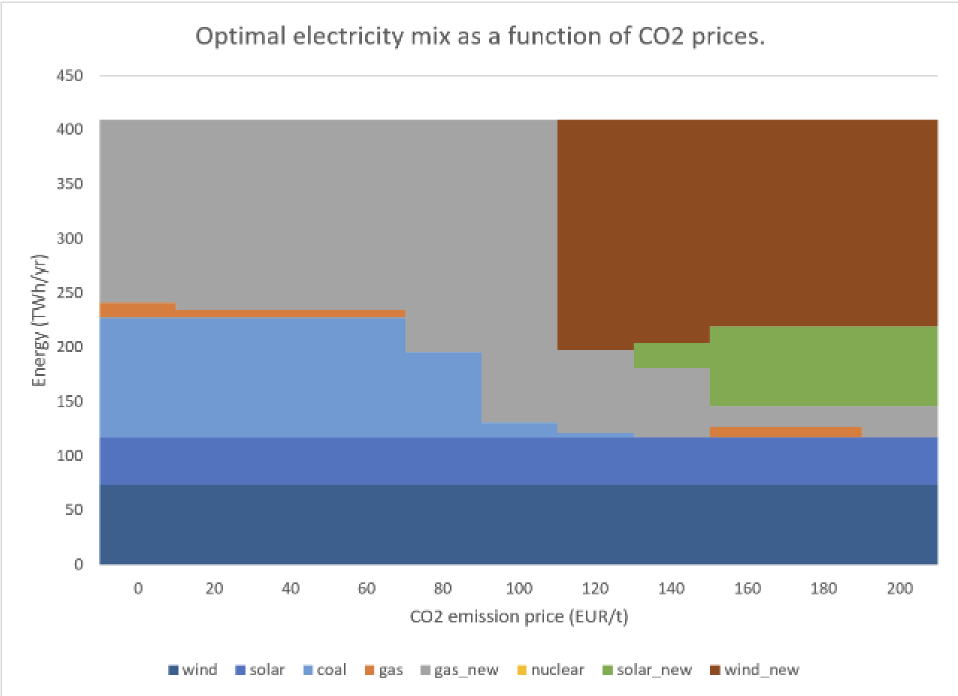



Figure task 6.a: Optimal electricity mix for increasing CO2 prices.

*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)*

<insert discussion here>

According to the results from task 2, new gas plants become competitive with respect to existing coal plants at CO2 prices between 80 and 100 EUR/t when running for between 2 and seasons, wind power becomes competitive with old coal power plants at around 90 EUR/t. Overall, strong shifts in the electricity mix between 80 and 120 EUR/t make a lot of sense.

*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)*

<insert discussion here>

Even though wind power is more expensive per unit of capacity, its higher capacity factors lead to lower levelized costs: All in all, we get more energy from wind power for our money. As long as there is not “too much” (see Exercise 8) wind power in the system, there is no reason to settle for less.

*Task 6.d (BONUS TASK), **3 points**: Qualitatively, what drives the increasingly important role of solar power starting from a certain $CO_2$ price? Hint: Get back to this question after working on Exercise 8. (60 words)*

| |
|---|
| <insert discussion here><br>Large amounts of wind power reduce the electricity prices during those seasons where it produces the most (winter, fall). Because of this, using larger shares of solar power becomes beneficial to provide power during the complementary seasons (spring, summer). |

## 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.*

<insert plot here>

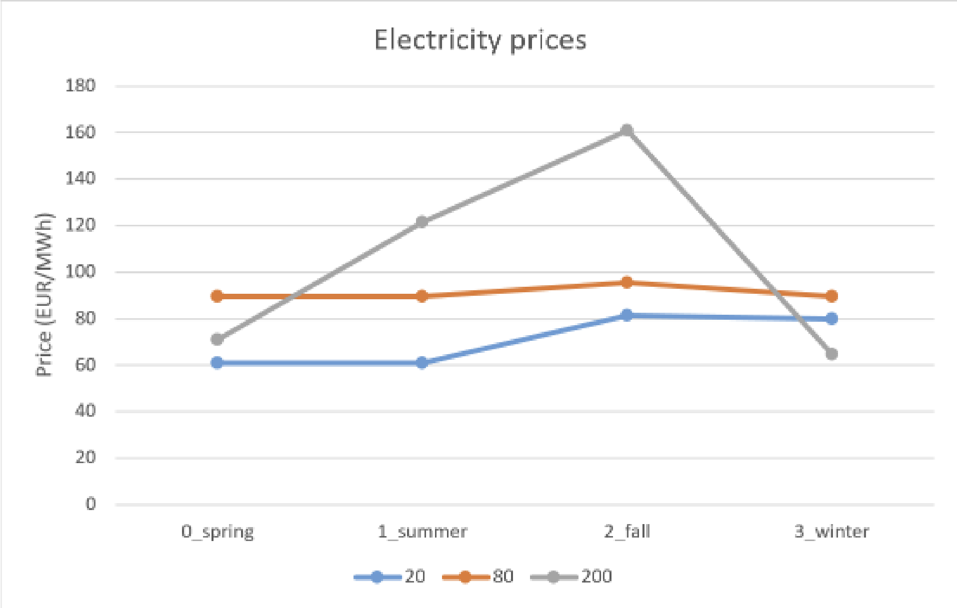



Figure Task 7.a: Electricity/Shadow prices by season for different CO2 emission prices.

*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)*

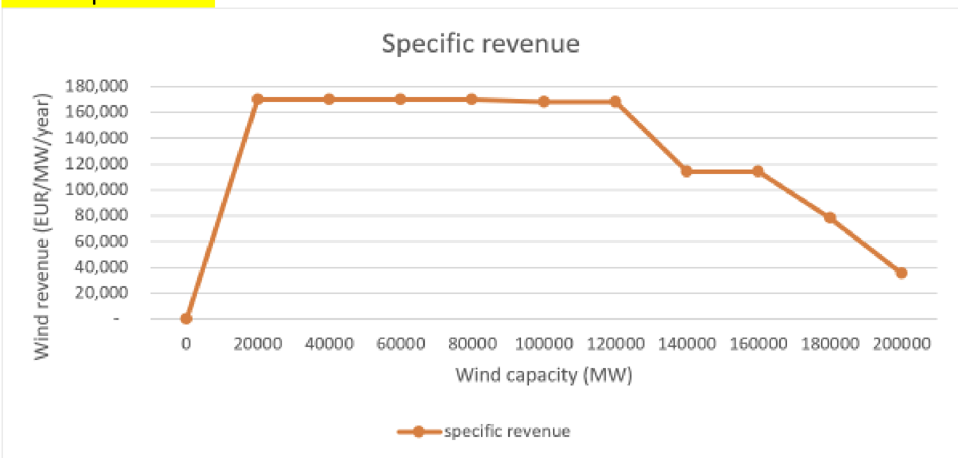
<insert discussion here>

Between 20 and 80 EUR/tCO2 no large shifts in the electricity mix occur (task 6.a). Here, the increase in electricity prices is just a consequence of higher CO2 prices. Note, however, that this increase is partly mitigated by a switch to more new gas power plant capacity (task 6.a). The dominant change between 80 and 200 EUR/tCO2 is the installation of larger wind and solar power capacity: Wind power produces electricity primarily in winter. This causes the large price drop during this season. In spring it is the mix of wind and solar production which depresses prices (seasonal capacity factors from task 2.e).

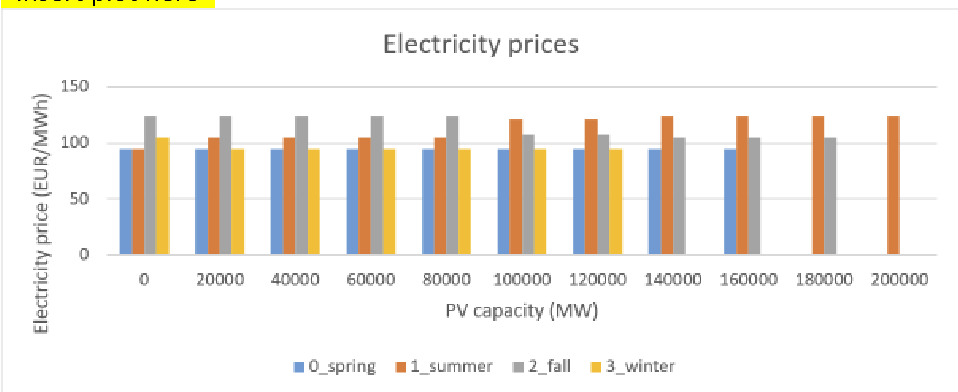
## Exercise 8: Specific value of wind power forced into the power system

*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).*

<insert plot here>



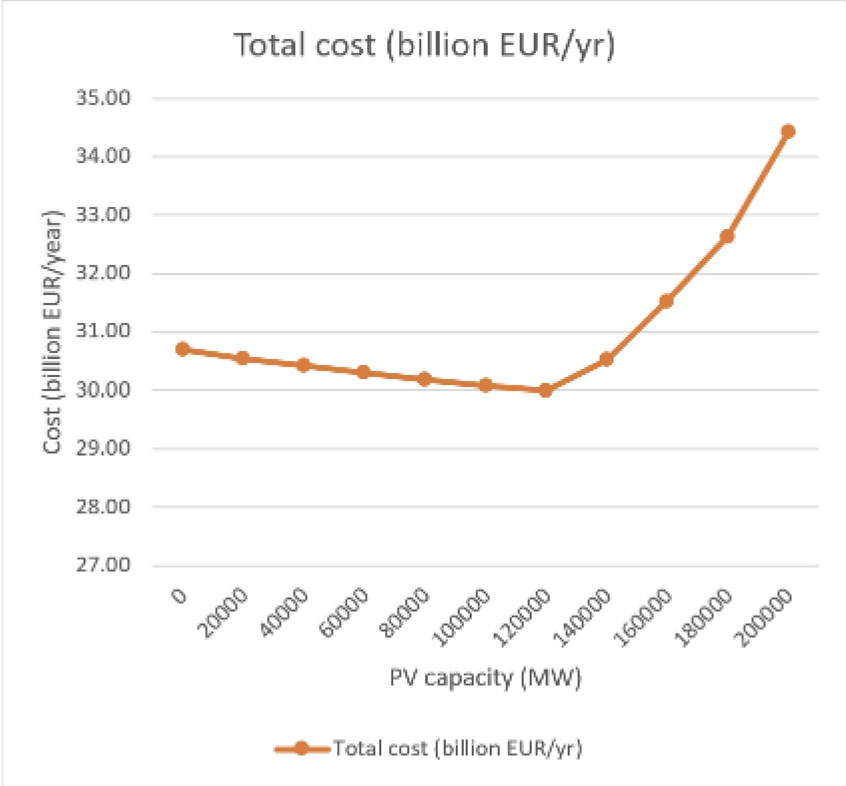

<insert plot here>




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).*

<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)*

<insert discussion here>

The total cost shows a clear minimum for a certain wind power capacity. This wind power capacity corresponds to the optimum. It is approximately equal to 120 GW of wind power. This is consistent with the result from exercise 6 (wind power capacity at a $CO_2$ emission price of 120 EUR/t). Both smaller and larger wind power capacities cause larger system costs: Larger capacities because they are too expensive to justify their installation, smaller capacities because the value of additional capacity would be higher than its cost.

*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)*

<insert discussion here>

- The specific revenue of wind power decreases for increasing wind turbine capacity. This reduction occurs stepwise.
- Electricity prices decrease stepwise as well. This is because wind power with zero variable cost replaces the production from the most expensive power plants first. This reduction in prices occurs first during the seasons with the greatest wind power production (fall and winter).

The reduction of the specific wind turbine capacity value/revenue is directly linked to the step-wise reduction of electricity prices. Specific value is specific production (=capacity factor * 2190) times prices.

Around the optimum (between 120 and 140 GW) the specific revenue drops from 168 EUR/MW/year to 114 EUR/MW/year. This suggests that the specific investment cost (164 EUR/MW/year) corresponds to the revenue at the optimum.

*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)*

<insert discussion here>

The old wind plants have the exact same capacity factor (produce the same amount of energy per unit of capacity installed) and earn the same amount of money per unit of electricity produced (same prices). Therefore, the specific revenue and its decrease are exactly the same.

*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)*

<insert discussion here>

Installing large amounts of the same inflexible resource (solar, wind) can lead to financing issues due to revenue erosion: The business case of new plants becomes more difficult (due to less expected revenue) or they require higher subsidies, the operators of old plants may run into difficulties if their plants generate less revenue than expected due to the addition of more capacity in the national grid over time. This is on top of technical grid-related issues which we don't consider here.

## 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)*

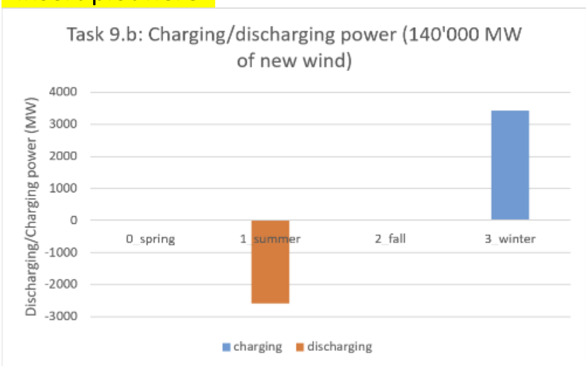
<insert discussion here>

- In the existing supply constraint, storage contributes both the supply (discharging) and the demand: (sum of power production) + discharging - charging >= demand
- The new storage constraint establishes a relation between the charged energy, charging and discharging: The energy stored during the current season must be equal the energy stored during the last season plus (charging times storage efficiency) minus discharging.

Here we assume that all losses are incurred during charging. We could also attribute them to discharging or partly to charging *and* discharging. In our case this does not matter since the energy capacity is unconstrained (only the total charging-discharging efficiency is relevant).

*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)..*

<insert plot here>




<insert plot here>

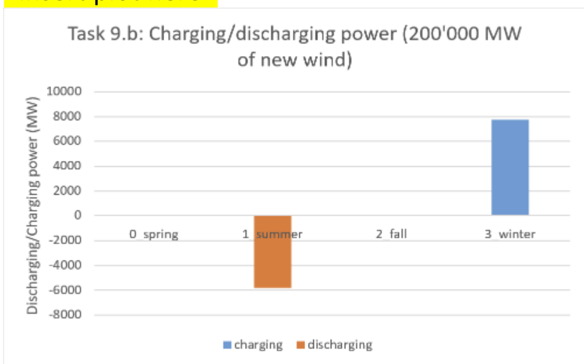



Figure Task 10.b: Charging and discharging power by season for two different wind capacities.

*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).*

<insert plot here>

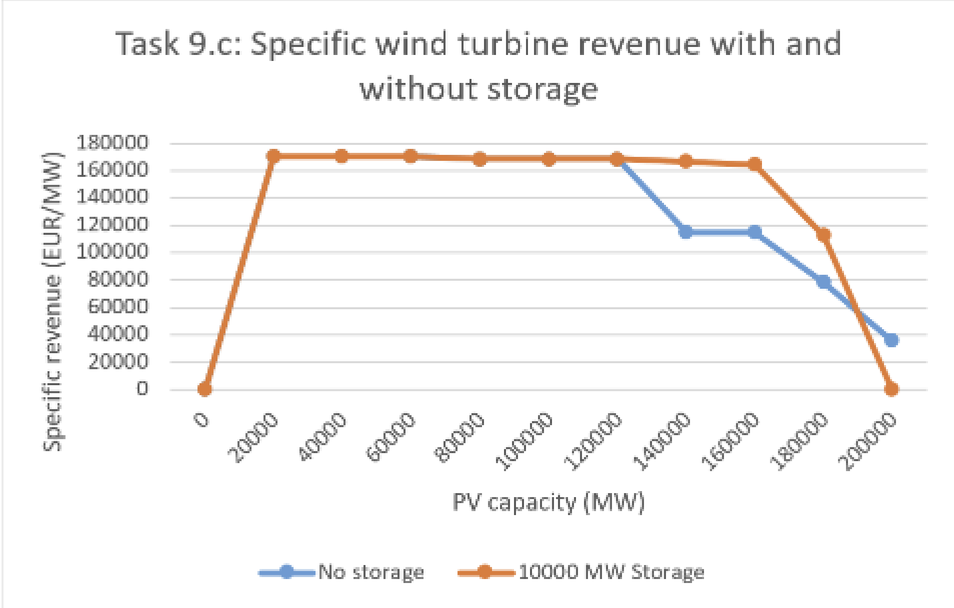
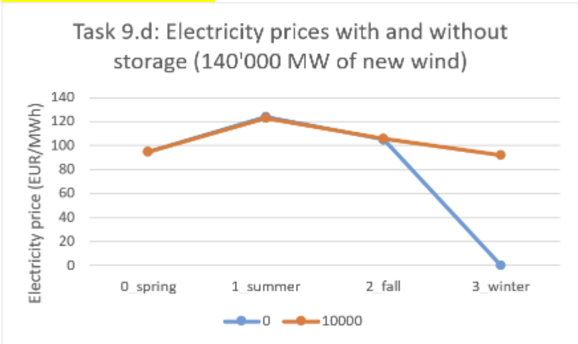


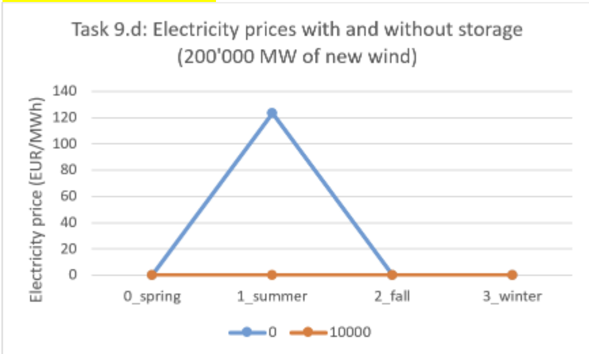

Figure Task 9.c: Specific PV revenue with and without storage.

*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.*

<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

*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)*

<insert discussion here>

- Figure Task 9.b shows that storage increases the wind power value for almost all wind power capacities (as long as it is active) and decreases wind power value for the largest capacity. Storage is inactive up to a wind power capacity of 120 GW.
- Wind power reduces the prices in winter and fall, when it produces the most energy (see capacity factors and Exercise 8). Storage transfers energy from winter to summer.

Because of this, prices generally get higher in winter (more demand!) and slightly lower in summer (discharging, more supply!)---figure task 9.d.

- Highest wind power capacity: If the wind power capacity is not too high, wind power in winter cannot provide all charging power at zero cost. In this case, prices do increase. This causes increasing wind power revenue. However, if wind power capacity is very high, prices in winter stay zero, despite the additional charging power demand. In this case, PV revenues decrease due to lower prices between spring and fall.