5XWA0 – Power System Analysis and Optimization

Assignment 3: Multi-period optimal power flow with energy storage

Minimum/Maximum Points: 0/10 (assignment weight 50%)

Deadline: 23:59 pm, June 26,2020

Consultation hours (no appointment needed):

Location: Zoom (same as for the lectures/instructions, details on Canvas), MSc Irena Dukovska

- 11/06/2020 14:00-15:00
- 18/06/2020 14:00-15:00
- 24/06/2020 14:00-15:00

General Instructions

The topic of Assignment 3 is an optimization problem for a power system for multiple periods of one day. The assignment consists of two parts. In the first part, you will study and analyze the theory and the mathematical formulation behind the optimization problem. In the second part, you will implement and solve the optimization problem in Python/Pyomo and analyze several case studies.

You will work in the same groups as for the previous assignments. If you wish to register a new group (max 2 students, only for unassigned students that missed the previous assignments) send an e-mail with the names of the students to n.paterakis@tue.nl in order to receive further instructions.

For this assignment you need to submit your version of the Jupyter Notebook from Part 2 and a short .pdf report discussing your findings from Part 1 and Part 2 using Canvas. Submit all the files as a single archive file (including ALL your input .xlsx files). Name your Jupyter Notebook as "PSAO2020_Assgn3_YourGroupNumber.ipynb", replacing "YourGroupNumber" with the actual number of your group.

Part 1 – Theoretical part

Instructions

In Assignment 3 you will study a large-scale optimization problem. For a given power system that consists of conventional generators, loads, photovoltaic parks (PV), wind parks (WP), and energy storage systems (ESS), we are interested in deciding the optimal schedule of all the components for each period of the following day. The objective is to minimize the total daily operating cost of the system, while the network and all its components operate within their technical limits.

In contrast with the optimization problems that we have seen up to now, in this model the optimal decisions in each time step depend on decisions in other time steps. In other words, this optimization problem comprises so-called inter-temporal constraints. Other than that, this optimization problem can be thought of as a multi-period combination of the Economic Dispatch, Unit Commitment and Optimal Power Flow problems.

The optimization model and the adopted notation are described next.

Some important notes:

- It is important to notice that the units of power are MW, while the units of energy are MWh. Due to the fact that the time step that we use in this case is 1h, unit conversions are implicit. For example, considering that $P_{i,t} = 10\ MW$ for some generator i in period t, it follows that the energy that is produced during the same period t is equal to $10MWh$.
- We are using a DC power flow approximation and therefore only the angle of the bus voltages and the active power flows are of interest. We assume that the common power system base that is used is 100 MVA. This implies that the optimal angles that are returned after having solved the optimization problem must be divided by 100.
- In order to simplify the problem it is assumed that only producing energy from conventional generators bears a cost. The PV and WP power is considered as must-take, whereas the costs of operating the ESS are not taken into account.

Notation

Indices		
i	Index of generators	
t	Index of time periods	
f	Index of steps of the generator cost functions	
s	Index of energy storage systems (ESS)	
j	Index of loads	
l	Index of transmission lines. Also, the notation $(n1, n2) \in l$ means that the sending and receiving buses of the line are $n1$ and $n2$, respectively.	
n	Index of buses	
k	Index of photovoltaic (PV) parks	
q	Index of wind parks	
I^n, S^n, J^n	are the sets of generators, ESS, loads connected to bus n	
K^n, Q^n	are the sets of PV parks, wind parks connected to bus n	
Parameters (inputs)		
P_i^{min}	Minimum power output of generator i	MW
P_i^{max}	Maximum power output of generator i	MW
RU_i	Ramp-up rate of generator i	MW/min
RD_i	Ramp-down rate of generator i	MW/min

SUC_i	Start-up cost of generator i	€
SDC_i	Shut-down cost of generator i	€
P_i^{ini}	Initial power output (before the first period) of generator i	MW
u_i^{ini}	Initial commitment status (before the first period) of generator i – 1 if generator i was online right before the beginning of the optimization horizon and 0 otherwise.	Binary parameter
$C_{i,f}$	Cost of energy from the f-th "power block" of generator i	€/MWh
$B_{i,f}$	Size of the f-th "power block" of generator i	MW
$D_{j,t}$	Demand of load j in period t	MW
$PV_{k,t}$	Generation of photovoltaic park k in period t	MW
$W_{q,t}$	Generation of wind park q in period t	MW
$P_s^{ESS,max}$	Maximum charging/discharging power of ESS s	MW
SOE_s^{max}	Maximum state-of-energy of ESS s (energy capacity of storage system)	MWh
SOE_s^{ini}	Initial state-of-energy of ESS s (before the first period)	MWh
η_s	Charging/discharging efficiency of ESS s	0-1 range
X_l	Reactance of transmission line l	Per-unit
$P_l^{line,max}$	Power transfer limit of transmission line l	MW
$B_{l,n}^{mat}$	Line-to-node incidence matrix. If n is a sending (from) bus for transmission line l the element (l, n) is $\frac{1}{X_l}$. If n is a receiving (to) bus for transmission line l the element (l, n) is $-\frac{1}{X_l}$. Otherwise the element (l, n) is zero.	Per-unit
Decision variables (outputs)		
$P_{i,t}$	Power output of generator i in period t	MW
$b_{i,f,t}$	Power used from the f-th "power block" of generator i in period t	MW
$u_{i,t}$	Commitment status of generator i in period t – 1 if generator i is online in period t and 0 otherwise.	Binary variable
$CSU_{i,t}$	Cost incurred by starting-up generator i in period t	€
$CSD_{i,t}$	Cost incurred by shutting-down generator i in period t	€
$SOE_{s,t}$	State-of-energy of ESS s in period t	MWh
$P_{s,t}^{ch}$	Charging power of ESS s in period t	MW
$P_{s,t}^{dis}$	Discharging power of ESS s in period t	MW
$u_{s,t}^{ESS}$	Charging behavior indicator variable of ESS s in period t – must be 1 in order to allow ESS s to charge in period t.	Binary variable
$f_{l,t}$	Active power flow through transmission line l in period t	MW
$\theta_{n,t}$	Angle of the voltage at bus n in period t	radians
TSC	Total system cost (the numerical evaluation of the objective function)	€

Mathematical formulation of the optimization problem

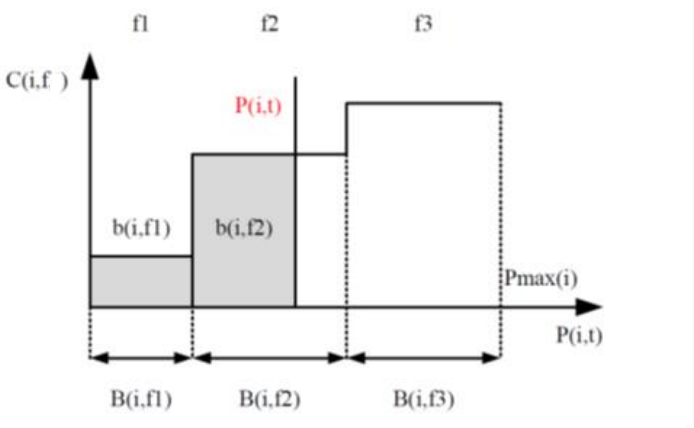
- **Modeling of the generators' marginal cost function**

The marginal cost function of a generator can be approximated as a non-decreasing step-wise constant function of their power output. In fact, this is in accordance with the way in which generating companies submit offers in the day-ahead electricity market.

The idea is to divide their power capacity in a number of blocks with size $B_{i,f}$, such that $\sum_f B_{i,f} = P_i^{max}$, each associated with a constant marginal cost $C_{i,f}$. Then, the power output of generator i in period t is composed by "filling up" the blocks up to the desired level. Evidently, some blocks are totally "filled up", while some others only partially (or not at all). For this reason a positive continuous decision variable $b_{i,f,t}$ (bounded by [0, $B_{i,f}$]) is introduced in order to indicate the amount of energy from each block that is being used in each period. For example, assume that for a generator the marginal cost function consists of three blocks f_1, f_2, f_3 with sizes $B_{i,f_1} = 10MW, B_{i,f_2} = 20MW, B_{i,f_3} = 30MW$. Then, a power output level of 15 MW in period t should be "filled up" as follows:

$$P_{i,t} = b_{i,f_1} + b_{i,f_2} + b_{i,f_3} \rightarrow 15 = 10 + 5 + 0$$

This approximation of the marginal cost function is illustrated in the following figure:



- **The mathematical formulation of the optimization problem is presented below:**

Objective function (minimize)

$$TSC = \sum_t \sum_i \left[\left(\sum_f C_{i,f} \cdot b_{i,f,t} \right) + CSU_{i,t} + CSD_{i,t} \right] \quad (1)$$

Constraints

GENERATING UNITS

$\mathrm{P_{i,t}} = \sum_{\mathrm{f}} \mathrm{b_{i,f,t}}$	$\forall$i, t	(2)
$0 \leq \mathrm{b_{i,f,t}} \leq \mathrm{B_{i,f}}$	$\forall$i, f, t	(3)
$\mathrm{P_i^{min}} \cdot \mathrm{u_{i,t}} \leq \mathrm{P_{i,t}} \leq \mathrm{P_i^{max}} \cdot \mathrm{u_{i,t}}$	$\forall$i, t	(4)
$\mathrm{P_{i,t}} - \mathrm{P_{i,(t-1)}} \leq 60 \cdot \mathrm{RU_i}$	$\forall$i, t > 1	(5)
$\mathrm{P_{i,t}} - \mathrm{P_i^{ini}} \leq 60 \cdot \mathrm{RU_i}$	$\forall$i, t = 1	(6)
$\mathrm{P_{i,(t-1)}} - \mathrm{P_{i,t}} \leq 60 \cdot \mathrm{RD_i}$	$\forall$i, t > 1	(7)
$\mathrm{P_i^{ini}} - \mathrm{P_{i,t}} \leq 60 \cdot \mathrm{RD_i}$	$\forall$i, t = 1	(8)
$CSU_{i,t} \geq SUC_i \cdot (u_{i,t} - u_{i,(t-1)})$	$\forall$i, t > 1	(9)
$CSU_{i,t} \geq SUC_i \cdot (u_{i,t} - u_i^{ini})$	$\forall$i, t = 1	(10)
$CSD_{i,t} \geq SDC_i \cdot (u_{i,(t-1)} - u_{i,t})$	$\forall$i, t > 1	(11)
$CSD_{i,t} \geq SDC_i \cdot (u_i^{ini} - u_{i,t})$	$\forall$i, t = 1	(12)

ENERGY STORAGE SYSTEM

$$SOE_{s,t} = SOE_{s,(t-1)} + \eta_s \cdot P_{s,t}^{ch} - \frac{P_{s,t}^{dis}}{\eta_s} \qquad \forall \text{s}, \text{t} > 1 \qquad (13)$$

$$SOE_{s,t} = SOE_{s}^{ini} + \eta_s \cdot P_{s,t}^{ch} - \frac{P_{s,t}^{dis}}{\eta_s} \qquad \forall \text{s}, \text{t} = 1 \qquad (14)$$

$$SOE_{s}^{min} \leq SOE_{s,t} \leq SOE_{s}^{max} \qquad \forall \text{s}, \text{t} \qquad (15)$$

$$P_{s,t}^{ch} \leq P_{s}^{ESS,max} \cdot u_{s,t}^{ESS} \qquad \forall \text{s}, \text{t} \qquad (16)$$

$$P_{s,t}^{dis} \leq P_{s}^{ESS,max} \cdot (1 - u_{s,t}^{ESS}) \qquad \forall \text{s}, \text{t} \qquad (17)$$

NETWORK CONSTRAINTS

$$\theta_{n,t} = 0 \qquad \forall t, n \text{ is the reference bus} \qquad (18)$$

$$-P_{l}^{line,max} \leq f_{l,t} \leq P_{l}^{line,max} \qquad \forall l, t \qquad (19)$$

$$f_{l,t} = B_{l,n_1}^{mat} \cdot (\theta_{n_1,t} - \theta_{n_2,t}) \qquad \forall\, l, t, (n1, n2) \in l \qquad (20)$$

NODAL POWER BALANCE

$$\sum_{k \in K^n} PV_{k,t} + \sum_{q \in Q^n} W_{q,t} + \sum_{s \in S^n} P_{s,t}^{dis} + \sum_{i \in I^n} P_{i,t} + \sum_{l|n=\binom{receiving}{end}} f_{l,t} = \sum_{j \in J^n} D_{j,t} + \sum_{s \in S^n} P_{s,t}^{ch} + \sum_{l|n=\binom{sending}{end}} f_{l,t} \qquad \forall n, t \qquad (21)$$

All the decision variables except for $f_{l,t}$ and $\theta_{n,t}$ are positive.

Equation (1) is the objective function of the problem and stands for the daily energy procurement cost from the generators, including commitment costs (start-up and shut-down costs) and needs to be minimized.

Constraints (2) and (3) model the decomposition of the generator's power output assuming a step-wise constant marginal cost function.

Constraint (4) enforces the minimum and maximum power output of generators.

Constraint (5) states that the power output of a generator in period t cannot be increased more than $60 \cdot RU_i$ with respect to the power output of the same generator in the previous period $(t-1)$. Constraint (6) is a special instance of (5) in the first period of the optimization horizon in which no previous period exists and therefore a given initial value must be used for the generator output (P_i^{ini}), else, $t-1$ would have been undefined. These are called "ramp-up" constraints and link variables in different time periods, i.e., they are intertemporal.

Constraints (7) and (8) are similar to (5) and (6) and model the ramp-down constraints of the generators.

Constraints (9) and (10) take into account the cost of starting-up a generator. Constraint (10) is a special instance of (9) for the first period of the optimization horizon. Each generator is associated with a fixed cost (SUC_i) that is incurred every time it is started-up. The variable $CSU_{i,t}$ takes the value SUC_i if and only if a generator is online in the current period ($u_{i,t} = 1$), but not in the previous one ($u_{i,(t-1)} = 0$). Else, it is zero. Note that (9) and (10) allow the variable $CSU_{i,t}$ to take any non-negative value (since $CSU_{i,t}$ is defined as a positive variable). However, due to the fact that this variable appears in the objective function to be minimized, it will take the minimum possible value, i.e., either SUC_i or zero.

Similarly to (9) and (10), constraints (11) and (12) take into account the cost of shutting-down a generator.

Constraints (13)-(17) constitute a simple ESS model. Constraint (13) updates the state-of-energy of the ESS in the current period t which is either increased by the amount of energy that is charged into the ESS, or decreased by the amount of energy that is discharged from the ESS, with respect to the state-of-energy of the ESS in the previous period $t-1$. Note that the ESS efficiency is also taken into account. Constraint (14) is simply an instance of (13) for the first period of the optimization horizon. Constraint (15) limits the state-of-energy within the capacity of the battery. Finally, (16) and (17) are a set of disjunctive constraints that prevent the battery from charging and discharging in the same period.

Constraints (18)-(20) represent the DC power flow approximation that is used to model the network constraints.

Finally, constraint (21) expresses the power balance at each node of the system.

QUESTIONS

Study carefully the optimization problem that was presented and provide your answers to the questions below.

I. Assume that a power system has the dimensions of the following table:

Set	**Number**
Time steps	24
Generators	2
Steps of generator cost functions	3
Energy storage systems	2
Loads	3
Transmission lines	7
Buses	5
PV parks	1
Wind parks	1

I.1. How many decision variables does the optimization problem have?

[0.25 points]

I.2. How many constraints associated with the ESS does the optimization problem have?

[0.25 points]

II. Explain how constraints (11) and (12) that take into account the shut-down cost of generators work.

[0.5 points]

III. The step-wise constant modeling of the marginal cost function of the generators is expressed by constraints (2) and (3). Constraint (2) states that the power output of a generating unit is decomposed into (parts of) energy blocks. However, it does not enforce the order in which these blocks must be covered. For example, assume that for a unit i we have:

$$\mathrm{B}_{\mathrm{i,f_1}} = 10\ \mathrm{MW}, \mathrm{B}_{\mathrm{i,f_2}} = 30\ \mathrm{MW}, \mathrm{B}_{\mathrm{i,f_3}} = 20\ \mathrm{MW}$$

Assume that $P_{i,t}$ in a period evaluates to 25 MW. In order for these constraints to serve our purposes, we want $b_{i,f_1} = 10\ MW, b_{i,f_2} = 15\ MW, b_{i,f_3} = 0\ MW$. Nonetheless, constraints (2) and (3) alone allow for any other (incorrect) combination to hold true. Note that for example the solution:

$$b_{\mathrm{i,f_1}} = 1\ \mathrm{MW}, b_{\mathrm{i,f_2}} = 10\ \mathrm{MW}, b_{\mathrm{i,f_3}} = 14\ \mathrm{MW}$$

satisfies both (2) and (3) for a fixed $P_{i,t} = 25\ MW$. Although it is a feasible solution of the problem, it does not satisfy the behavior that is being modeled.

Explain why the particular optimization model is capable of decomposing the generating unit power output correctly without the need of additional constraints apart from (2) and (3).

[1 point]

IV. Explain the meaning of equation (21). Suppose that we want to solve the same problem without considering the network constraints and only consider the total system balance instead of the nodal balance. Provide the equality constraint by which (21) should be replaced.

[1.5 points]

Part 2 – Implementation part

Instructions

In this part you must implement the optimization model that was presented in Part 1 using Python/Pyomo and conduct a number of studies on a modified version of the IEEE Reliability Test System – 1996[1].

This system consists of 24 buses, 34 transmission lines and 32 conventional generators of various technologies (types). An explanation of the generator Type codes is provided in the following Table:

Type code	**U12**	**U20**	**U50**	**U76**	**U100**	**U155**	**U197**	**U350**	**U400**
Technology	Oil/Steam	Oil/Combustion Turbine	Hydro	Coal/Steam	Oil/Steam	Coal/Steam	Oil/Steam	Coal/Steam	Nuclear

In addition to that, renewable generation plants are considered for construction and connection at Bus 14. The energy produced by these plants is considered to be must-take energy (i.e., it is considered as "negative load") at zero cost. Due to the favorable conditions, the investor is considering two different resources: a photovoltaic (PV) park and a wind park. The total generation of the two different parks in MW is given in Figure 1. Also, an energy storage system (ESS) with an energy capacity of 490 MWh is connected to the same bus. The round-trip efficiency of the storage facility is 95%. At the beginning of the day the state-of-energy of the storage system is 20 MWh. The total demand of the load is also portrayed in Figure 1. In every period, each of the 17 loads connected at different buses consumes a fixed percentage of the total system demand.

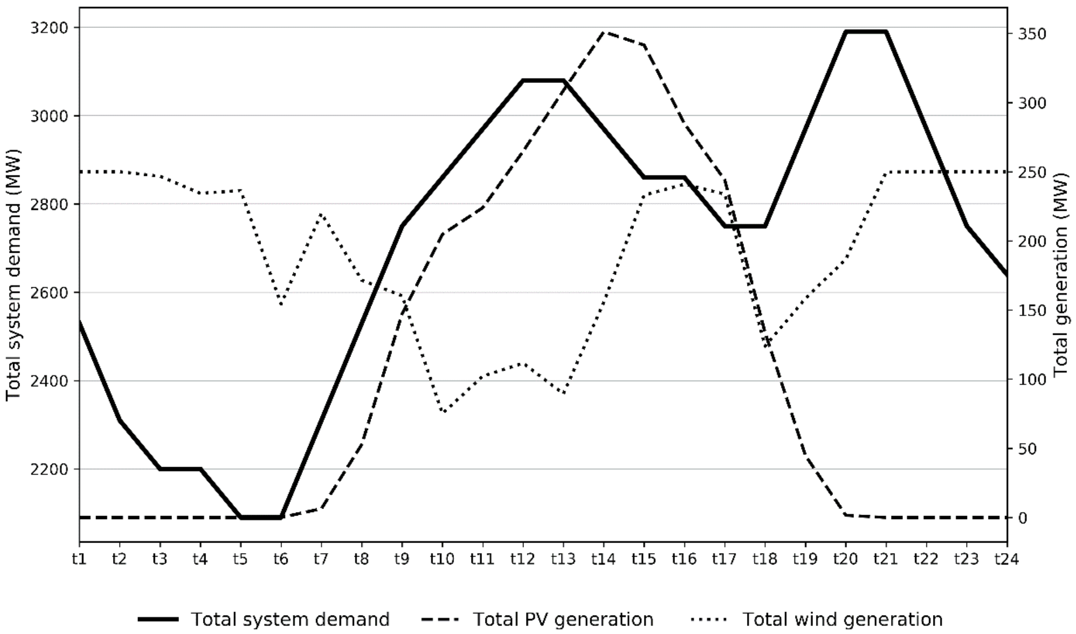


Figure 1. Total system demand and PV generation.

All the necessary data in order to conduct simulations on this power system are given in the MS Excel file **Input_Files\Assignment3_InputData.xlsx**. The units of the numerical values are the same as the ones of the parameters defined in Part 1. Also, the base for apparent power is considered to be 100 MVA.

[1] The IEEE Reliability Test System – 1996. *IEEE Transactions on Power Systems*, vol. 14, no. 3, August 1999.

A description of the different sheets can be found in the following table:

Sheet	Description
NetworkData	Contains data regarding the transmission system, the transmission lines, their sending and receiving bus, the reactance and their capacity.
SystemDemand	Contains data regarding the total system demand that should be split across the loads.
PVGeneration	Contains data regarding the total system PV generation that should be across the PV parks.
Wind Generation	Contains data regarding the total system wind generation that should be across the wind parks.
Loads	Contains data regarding the location of the loads and the percentage of the total system demand each load consumes.
PVParks	Contains data regarding the location of PV parks and the percentage of the total system PV generation each PV park generates.
WindParks	Contains data regarding the location of wind parks and the percentage of the total system wind generation each PV park generates.
StorageSystems	Contains data regarding the power and energy rating of the ESS, the initial state-of-energy, the round-trip efficiency and their location.
Generators	Contains data regarding the generators, their type, their maximum and minimum power output, the start-up and shut-down costs, the ramp-up and ramp-down rates, the initial commitment status and initial power output, as well as their location.
GeneratorStepSize	Contains data regarding the size of each power block of the generators' cost function (notice that they add up to the maximum power output of the corresponding generator).
GeneratorStepCost	Contains data regarding the cost of each step of the generators' marginal cost function (notice that they are strictly non-decreasing).

In the directory **Helper_Functions** you can find a .py file (python code) containing a method that allows you to write an Excel file containing the optimal values of all the decision variables (apart from $b_{i,f,t}$ and the TSC).

You will work in the same groups as for the previous assignments. If you wish to register a new group (max 2 students, only for unassigned students that missed the previous assignments) send an e-mail with the names of the students to n.paterakis@tue.nl in order to receive further instructions.

Section I – Implementation

Implement the optimization model using Python/Pyomo by completing the Jupyter Notebook file that was provided. More specifically, you need to complete the method optimizationModel() which returns the optimization model. Make sure that you carefully follow the instructions that are given as comments in the corresponding sections of the Jupyter Notebook.

I.1. Define the parameters related to the generators (10 parameters) in Section #Define Parameters.

[0.25 points]

I.2. Initialize the parameters related the generators and allocate the total system load to the buses in Section #Initialize Parameters.

[0.25 points]

I.3. Define the decision variables related to the energy storage system (4 variables) in Section #Define the Decision Variables.

[0.5 points]

I.4. Complete the following constraints and add them to the model in Sections #Define Constraints and #Add Constraints to the Model, respectively:

- def RampDownConstraint()
- def ShutDownCost()
- def ESS_SOEupdate(). This constraint needs to be completed such that the update rule is defined for every $t > 1$.
- def Balance(). This constraint must be added in order to replace pf_rule() when no network constraints are considered. This is equivalent to the expression that you proposed in Question IV of Part I.

Since the model is constructed using a method, it can be used in order to investigate different cases in which not all the constraints are considered. More specifically, in Question II.1. three cases are defined. Conditionally add constraints to the model in order to be able to simulate the different cases based on the value of the "modelType" argument.

[1 point]

A small-scale test system the characteristics of which can be found in **Input_Files\Assignment4_ValidationSystem.xlsx** is provided in order to verify that your implementation is correct. The model is solved for all Cases of Question II.1. The results that you should obtain (optimal decision variable values) can be found in the corresponding .xlsx files **Validation_System_Results\DecisionVariablesValidation_Case#.xlsx**. The optimal objective function values for the corresponding cases are given in **Validation_System_Results\ObjFunctionValue_Validation.txt**

Section II – Basic simulations

Initially the PV park, the wind park, and the ESS are **NOT** connected to the power system.[2]

II.1.: For the following cases:

Case	Network constraints	Generator ramping constraints	Transmission line limits
Case 1	No	No	-
Case 2	Yes	Yes	Yes
Case 3	Yes	Yes	No

A) Report and compare the total operating cost of the system in the following cases.

B) For each generator type (per type code) compute and comment on:
   - the total daily energy generation
   - the total daily energy costs
   - the total daily commitment costs (i.e., start-up and shut-down costs)

[1 point]

II.2. Case 3 considers the same constraints as Case 2 with the difference that in Case 3 the transmission line flow limits are relaxed. As a result, in the optimal decisions that are made in Case 3 may lead to overloading of several transmission lines. Produce two visualizations (e.g., heatmaps), one for each case, that for each time period indicate the degree of loading of each transmission line in Cases 2 and 3, respectively. At least the following should be evident for each time period:

- The transmission lines that are loaded below 50% of their capacity.
- The transmission lines that are loaded between 50% and 80% of their nominal capacity.
- The transmission lines that are loaded between 80% and 100% of their nominal capacity.
- The transmission lines that are loaded above 100% their nominal capacity.

Comment on the differences in transmission line loading between the two cases.

[0.5 points]

[2] The easiest way to simulate this condition is to create a new input file (copy of the provided one) in which you set 0 in the Percentage of PV1 in the sheet named "PVparks", 0 in the Percentage of WP1 in the sheet named "Windparks" and 0 in the Power of ESS1 in the sheet named "StorageSystems", respectively.

Section III – The effect of renewable generation and the ESS

The addition of renewable energy plants will be considered in the power system. Use the original input data file and where it is needed, modify the power rating of the ESS. Two scenarios will be considered:

1) PV park and the ESS are connected to the power system. The wind park is not connected.
2) Wind park and ESS are connected to the power system. The PV park is not connected.

III.1. First, consider a scenario where the PV park and the ESS are connected to the power system. The wind park is not connected. Perform the simulations for Case 2 and Case 3 and answer the questions bellow.

Then, consider a scenario where there a wind park and ESS are connected to the power system. The PV park is not connected. Perform the simulations for Case 2 and Case 3 for this scenario and answer the questions bellow. In both scenarios, assume that the ESS has a power rating of 70 MW (7 hours charge/discharge).

A) For the conditions of Case 3 plot the state-of-energy of the ESS together with the original total system load demand in the same figure. How can the charging/discharging behavior of the ESS be explained?
B) For the conditions of Case 2 plot the state-of-energy of the ESS together with the original total system load demand in the same figure. How are these results different in comparison with Question III.1.A? What is a potential cause of this behavior?

Finally, compare the charging/discharging behavior of the ESS for both Case 2 and Case 3 for the two scenarios, one with PV park and ESS and the other with wind park and ESS. Comment on the similarities and differences.

[1 point]

III.2. The System Operator is investigating the possibility of increasing the power rating of the energy storage facility that is connected at Bus 14. For this purpose, consider a power rating of the 490 MWh storage facility such that it can be charged or discharged in 7 or in 1 hour. For the two scenarios, determine the reduction in the total system cost with respect to a case in which the PV park/wind park is connected to the system, whereas the ESS is not. In addition, compare the total system costs with respect to the case when there was not renewable generation in the power system. In this question consider both Cases 2 and 3 and compare your results.

To determine the corresponding nominal power rating in each case, assume that the efficiency of the ESS is 100%. The efficiency during the simulations should be still considered equal to 95%.

Finally, for Case 2 and considering an ESS with 1h discharge, plot the original total system load demand (from the input file) and the resulting total system load demand considering the effect of storage charging and discharging power (charging is a load, discharging is a “negative” load) in the same figure. Do this for the two scenarios, one with PV park and one with wind park. What do you observe? Comment on the similarities and differences.

[1.5 points]

Reporting

Prepare a short report answering the questions from Part 1 and Part 2. The report is assessed on the basis of its readability. There is not a mandatory template for the report. However, a sample template is available on Canvas.

[0.5 points]