IE453 – Energy Systems Planning

Homework 3 - Report

Group 15

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First question:

First thing we did is to convert all units to KWh as follows.

Demand(KWh)	SolarOutput (generated) (KWh/m^2.day)
13380.00	0.44747375
12900.00	0.47100625
12780.00	0.58492625

In this setting, when we divide demand by solar output, we obtain the minimum panel size required to meet the demand at that day. If we want to meet the demand in all days, we need to take the maximum of minimum panel size required values, in that way we guarantee to not miss any demand. To accomplish this, we need to install 267,646.4232 m^2 solar panel. Then we multiply with this size (m^2) with solar output generation (KWh/m^2) to find the total solar generation. We subtract demand from the solar generation in each day to find the spill at that day, and their summation gives us the total spill in this time frame.

To find the total spill(**KWh**):	8869192.183		
in megawatts:	8869.192183		
demand(kwh)	solaroutput(kwh/m2)	actual output(output*size)	Spills:
13380	0.44747375	119764.7486	106384.7
12900	0.47100625	126063.1381	113163.1
12780	0.58492625	156553.4186	143773.4

Only first three columns are given just for illustration purposes. As one can see above, total spill is **8,869,192 KWh**, which corresponds to **8869.19 MWh**. Total cost in this setting is equal to [panel size*panel cost per m^2] = [8,869,192 * $200] = **$1,773,838,400.**

Second question:

Here is the linear programming model we developed for the problem:

LP model:

$$\min \quad C_s \times PanelSize \times \left(\frac{0.015}{1-(1.015)^{-180}}\right) + C_d \times \sum_{i=1}^{60} GridUsage_i$$

s.t.

$$SR_t \times PanelSize = SolarUsed_t + SolarCurtailed_t$$

$$Demand_t = SolarUsed_t + GridUsage_t$$

All variables are nonnegative.

Parameters:

C_s : cost of the panel per m^2.

C_d : cost of grid electricity per KWh.

SR_r : solar generation at time t.

$Demand_t$: demand at time t.

Decision variables:

PanelSize : size of the solar panel to be installed (m^2).

$GridUsage_t$: amount of grid electricity consumption at time t.

$SolarUsed_t$: solar energy used at time t.

$SolarCurtailed_t$: solar energy curtailed at time t.

We solved our model via IBM CPLEX 12.10.

- The size of the solar panel is **21,710 m^2**.
- Total cost is equal to **$82,270.823.**
- This system is **$1,773,756,129** cheaper than the solar-only system in the first question.

- **6.15%** of the demand is satisfied from the grid while the rest **(93.85%)** is satisfied from the solar panel.
- Total solar energy spilled in this case is **81,386 KWh**.
- Calculations can be found in the Excel sheet (which is submitted along with this report) named "percentage calculation".

Third question:

We only changed the following constraint

from $Energy\_curtailed_t >= 0$ to $Energy\_curtailed_t == 0$.

- Size of the solar panel dropped to **11,300 m^2.**
- This time 45.46% of the demand is satisfied from the grid. The reason is that we didn't allow any curtailment and forced the model to use grid electricity.
- Total cost is **$127,722.234.**

Fourth question:

As suggested in the question, we introduced a new variable called "shifted_energy". This variable stands for the amount of demand that is shifted to the next day. When modifying the model, we are take the model that Selin Hoca wrote down in the lectures into account. The following is the updated constraint set (objective function is the same) (newly added constraints are marked red):

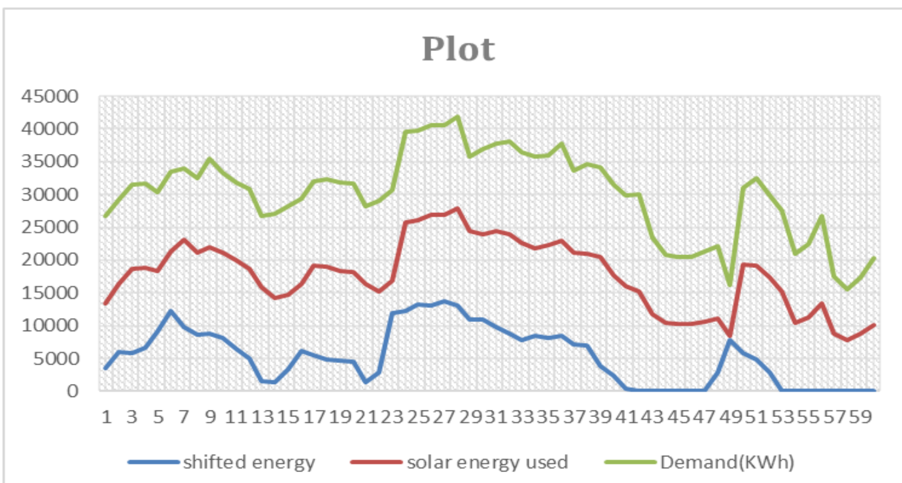
```
panel_size >= 0;

shifted_energy[0] == 0;

forall(i in time)
  shifted_energy[i] >= 0;

shifted_energy[60] == 0;

forall(i in time)
  shifted_energy[i] <= Hourly_demand[i];


forall (i in time)
    Grid_usage[i] >= 0;

forall (i in time)
    Solar_energy_used[i] >= 0;
forall (i in time)
    (Energy_curtailed[i]) >= 0;
```

```
    forall (i in time)
      Generation_constraint:
        Energy_generation[i]*panel_size == Solar_energy_used[i] +
Energy_curtailed[i];

       forall (i in time)
      Demand_constraint:
        Hourly_demand[i] + shifted_energy[i-1] - shifted_energy[i] ==
Solar_energy_used[i] + Grid_usage[i] ;

}
```

We solve the model via CPLEX again and obtained the following:

- Size of the solar panel is now **22,130 m^2**.
- Overall cost is **$72,030.**

We also plotted daily demand, shifted energy and solar energy used in the same plot as suggested in the homework:



Observations:

- In this load shifting model, we have the flexibility to tell the customers to postpone their daily demands and this enables us to exploit solar radiation better. It is not a coincidence that this model proposes a bigger solar panel size than the previous models. The solar energy becomes way more useful because we eradicate the intermittency problem to a certain extent.
- In load shifting model, the grid usage is very low. We use grid only in two days and the total amount we consume from the grid is approximately **2700 KWh**. This is also a result that we would expect. Grid is like the secondary source of electricity in this system and we utilize it only when we can't meet the current demand with solar energy. In this setting, as we utilize the solar energy more

efficiently, there is no need to use the grid compared to the previous (**non** load-shifting) models. The size of the solar panel is bigger but the grid consumption is very low, so the overall cost is dropped by **~ $9800** compared to the model in the second question.

- The plot also does make sense. To conclude, we can say that the load shifting model is realistic, useful and enabled us to lower our cost.

Fifth question:

In this model, now we have the flexibility to postpone the demand for two days, not just one day. To adopt this change in our model we modified our as follows (changes marked red):

```
subject to{

   panel_size >= 0;

   shifted_energy_2[0] == 0;

   shifted_energy_2[60] == 0;

   shifted_energy_2[59] ==0;

   shifted_energy_2[-1] == 0;

   shifted_energy[0] == 0;

   forall(i in time)
     shifted_energy[i] >= 0;
   forall(i in time)
     shifted_energy_2[i] >= 0;

   shifted_energy[60] == 0;

   forall(i in time)
     shifted_energy[i] <= Hourly_demand[i];

   forall (i in time)
       Grid_usage[i] >= 0;

   forall (i in time)
       Solar_energy_used[i] >= 0;
   forall (i in time)
       (Energy_curtailed[i]) >= 0;

   forall (i in time)
     Generation_constraint:
       Energy_generation[i]*panel_size == Solar_energy_used[i] +
Energy_curtailed[i];

       forall (i in time)
     Demand_constraint:
```

```
        Hourly_demand[i]  + shifted_energy_2[i-2] + shifted_energy[i-1] - 
shifted_energy[i] - shifted_energy_2[i] == Solar_energy_used[i] + Grid_usage[i];

}
```

The model is basically the same as the previous one, only change is that we added a new variable called "shifted_energy_2" to account for the amount of energy shifted to the day after tomorrow. In this setting:

- The total cost is **$66,729.4.**
- The size of the solar panel is **20,718 m^2.**
- Grid usage is zero.

As expected, the total cost is less than that of fourth question. The reason for this is, in addition to Q4, the load can be shifted for two days, therefore grid usage is zero.