Supplementary Files

Name	Robin Pilling
Title	Shapley Value-based Payment Calculation for Energy Exchange between Micro- and Utility Grids
Submission	29.07.2017
Supplementary file list	The supplementary files containing a total of three parts ● Part 1: Data (Database) ● Part 2: Drawings from analysis (Excel) ● Part 3: : Smart Grid Operations (CPLEX Algorithm) - *3.1 Microgrid Generation (No Storage)* - *3.2 Microgrid Generation (Storage)* - *3.3 Utility Generation* - *3.4 Joint Generation (No Storage)* - *3.5 Joint Generation (Storage)*

Part 1: Data

- **Pecan Street Research Dataport** (https://dataport.pecanstreet.org/)

Our results are presented for the residential load and PV generation data obtained for the Mueller community as of April 2015. We executed the query and exported data from the Pecan Street Data base at April 13, 2015. To query the database, users must register online. Figure 1 illustrates the data query process:

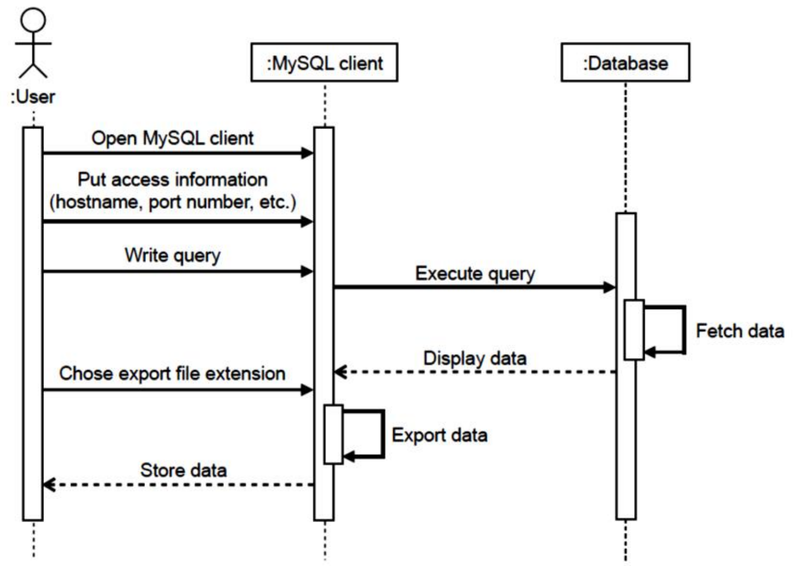
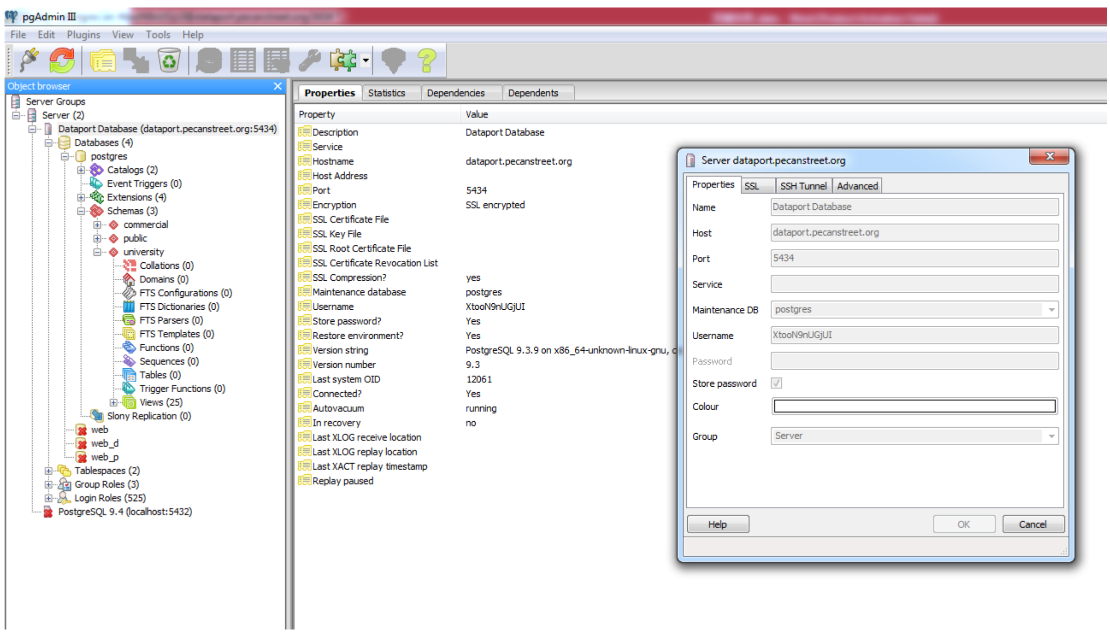


Figure 1. A data access sequence diagram for the Pecan Street Database using a MySQL client

We use pgAdminIII (http://www.pgadmin.org/) as MySQL client to query the database.

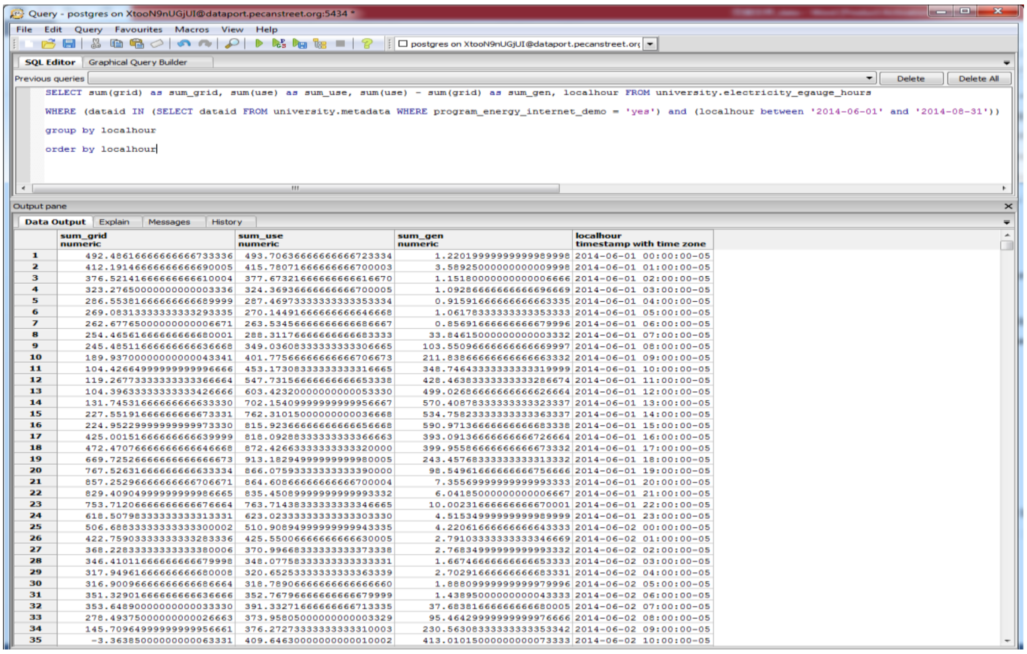


- **Microgrid Load**

a. Pecan Street Dataport Query

The query extracts the sum of the whole home consumption (sum(use) as sum_use) for a certain period of time (localhour between 'YYYY-MM-DD' and ' YYYY-MM-DD ') as an aggregate function for the single-family homes which participated in the Mueller microgrid (Energy Demonstration Project) (program_energy_internet_demo = 'yes'). For convenience, the data is then grouped and ordered by local hour.

<u>SQL Query for the summer scenario:</u>



	sum_grid numeric	sum_use numeric	sum_gen numeric	localhour timestamp with time zone
1	492.48616666666666733336	493.70636666666666723334	1.22019999999999989998	2014-06-01 00:00:00-05
2	412.19146666666666690005	415.78071666666666700003	3.58925000000000009998	2014-06-01 01:00:00-05
3	376.52141666666666610004	377.67321666666666616670	1.15180000000000006666	2014-06-01 02:00:00-05
4	323.27650000000000003336	324.36936666666666700005	1.09286666666666696669	2014-06-01 03:00:00-05
5	286.55381666666666689999	287.46973333333333353334	0.91591666666666663335	2014-06-01 04:00:00-05
6	269.08313333333333293335	270.14491666666666646668	1.06178333333333353333	2014-06-01 05:00:00-05
7	262.67765000000000006671	263.53456666666666686667	0.85691666666666679996	2014-06-01 06:00:00-05
8	254.46561666666666680001	288.31176666666666683333	33.84615000000000003332	2014-06-01 07:00:00-05
9	245.48511666666666636668	349.03608333333333306665	103.55096666666666669997	2014-06-01 08:00:00-05
10	189.93700000000000043341	401.77566666666666706673	211.83866666666666663332	2014-06-01 09:00:00-05
11	104.42664999999999996666	453.17308333333333316665	348.74643333333333319999	2014-06-01 10:00:00-05
12	119.26773333333333366664	547.73156666666666653338	428.46383333333333286674	2014-06-01 11:00:00-05
13	104.39633333333333426666	603.42320000000000053330	499.02686666666666626664	2014-06-01 12:00:00-05
14	131.74531666666666633330	702.15409999999999956667	570.40878333333333323337	2014-06-01 13:00:00-05
15	227.55191666666666673331	762.31015000000000036668	534.75823333333333363337	2014-06-01 14:00:00-05
16	224.95229999999999973330	815.92366666666666656668	590.97136666666666683338	2014-06-01 15:00:00-05
17	425.00151666666666639999	818.09288333333333366663	393.09136666666666726664	2014-06-01 16:00:00-05
18	472.47076666666666646668	872.42663333333333320000	399.95586666666666673332	2014-06-01 17:00:00-05
19	669.72526666666666666673	913.18294999999999980005	243.45768333333333313332	2014-06-01 18:00:00-05
20	767.52631666666666633334	866.07593333333333390000	98.54961666666666756666	2014-06-01 19:00:00-05
21	857.25296666666666706671	864.60866666666666700004	7.35569999999999993333	2014-06-01 20:00:00-05
22	829.40904999999999986665	835.45089999999999993332	6.04185000000000006667	2014-06-01 21:00:00-05
23	753.71206666666666676664	763.71438333333333346665	10.00231666666666670001	2014-06-01 22:00:00-05
24	618.50798333333333313331	623.02333333333333303330	4.51534999999999989999	2014-06-01 23:00:00-05
25	506.68833333333333300002	510.90894999999999943335	4.22061666666666643333	2014-06-02 00:00:00-05
26	422.75903333333333283336	425.55006666666666630005	2.79103333333333346669	2014-06-02 01:00:00-05
27	368.22833333333333380006	370.99668333333333373338	2.76834999999999993332	2014-06-02 02:00:00-05
28	346.41011666666666679998	348.07758333333333333331	1.66746666666666653333	2014-06-02 03:00:00-05
29	317.94961666666666680008	320.65253333333333363339	2.70291666666666683331	2014-06-02 04:00:00-05
30	316.90096666666666686664	318.78906666666666666660	1.88809999999999979996	2014-06-02 05:00:00-05
31	351.32901666666666636666	352.76796666666666679999	1.43895000000000043333	2014-06-02 06:00:00-05
32	353.64890000000000033330	391.33271666666666713335	37.68381666666666680005	2014-06-02 07:00:00-05
33	278.49375000000000026663	373.95805000000000003329	95.46429999999999976666	2014-06-02 08:00:00-05
34	145.70964999999999956661	376.27273333333333310003	230.56308333333333353342	2014-06-02 09:00:00-05
35	-3.36385000000000063331	409.64630000000000010002	413.01015000000000073333	2014-06-02 10:00:00-05

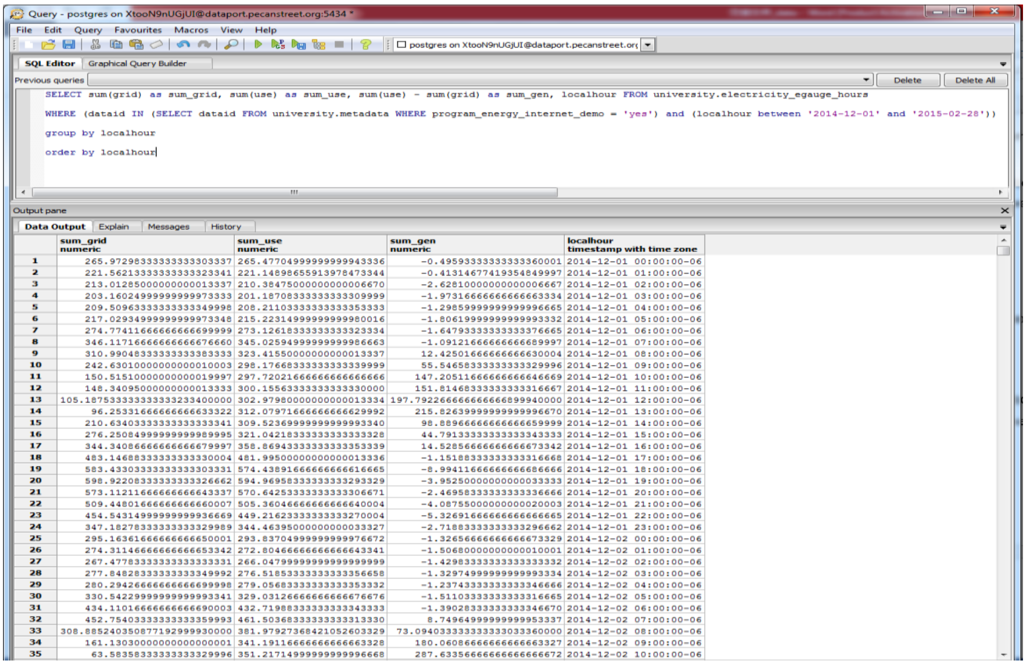
SELECT sum(grid) as sum_grid, sum(use) as sum_use, sum(use) - sum(grid) as sum_gen, localhour FROM university.electricity_egauge_hours

WHERE (dataid IN (SELECT dataid FROM university.metadata WHERE program_energy_internet_demo = 'yes') and (localhour between '2014-06-01' and '2014-08-31'))

group by localhour

order by localhour

<u>SQL Query for the winter scenario:</u>



	sum_grid numeric	sum_use numeric	sum_gen numeric	localhour timestamp with time zone
1	265.97298333333333303337	265.47704999999999943336	-0.49593333333333360001	2014-12-01 00:00:00-06
2	221.56213333333333323341	221.14898655913978473344	-0.41314677419354849997	2014-12-01 01:00:00-06
3	213.01285000000000013337	210.38475000000000006670	-2.62810000000000006667	2014-12-01 02:00:00-06
4	203.16024999999999973333	201.18708333333333309999	-1.97316666666666663334	2014-12-01 03:00:00-06
5	209.50963333333333349998	208.21103333333333353333	-1.29859999999999996665	2014-12-01 04:00:00-06
6	217.02934999999999973348	215.22314999999999980016	-1.80619999999999993332	2014-12-01 05:00:00-06
7	274.77411666666666699999	273.12618333333333323334	-1.64793333333333376665	2014-12-01 06:00:00-06
8	346.11716666666666676660	345.02594999999999986663	-1.09121666666666689997	2014-12-01 07:00:00-06
9	310.99048333333333383333	323.41550000000000013337	12.42501666666666630004	2014-12-01 08:00:00-06
10	242.63010000000000010003	298.17668333333333339999	55.54658333333333329996	2014-12-01 09:00:00-06
11	150.51510000000000019997	297.72021666666666666666	147.20511666666666646669	2014-12-01 10:00:00-06
12	148.34095000000000013333	300.15563333333333330000	151.81468333333333316667	2014-12-01 11:00:00-06
13	105.18753333333333233400000	302.97980000000000013334	197.79226666666666899940000	2014-12-01 12:00:00-06
14	96.25331666666666633322	312.07971666666666629992	215.82639999999999996670	2014-12-01 13:00:00-06
15	210.63403333333333333341	309.52369999999999993340	98.88966666666666659999	2014-12-01 14:00:00-06
16	276.25084999999999989995	321.04218333333333333328	44.79133333333333343333	2014-12-01 15:00:00-06
17	344.34086666666666679997	358.86943333333333353339	14.52856666666666673342	2014-12-01 16:00:00-06
18	483.14688333333333330004	481.99500000000000013336	-1.15188333333333316668	2014-12-01 17:00:00-06
19	583.43303333333333303331	574.43891666666666616665	-8.99411666666666686666	2014-12-01 18:00:00-06
20	598.92208333333333326662	594.96958333333333293329	-3.95250000000000033333	2014-12-01 19:00:00-06
21	573.11211666666666643337	570.64253333333333306671	-2.46958333333333336666	2014-12-01 20:00:00-06
22	509.44801666666666660007	505.36046666666666640004	-4.08755000000000020003	2014-12-01 21:00:00-06
23	454.54314999999999936669	449.21623333333333270004	-5.32691666666666666665	2014-12-01 22:00:00-06
24	347.18278333333333329989	344.46395000000000033327	-2.71883333333333296662	2014-12-01 23:00:00-06
25	295.16361666666666650001	293.83704999999999976672	-1.32656666666666673329	2014-12-02 00:00:00-06
26	274.31146666666666653342	272.80466666666666643341	-1.50680000000000010001	2014-12-02 01:00:00-06
27	267.47783333333333333331	266.04799999999999999999	-1.42983333333333333332	2014-12-02 02:00:00-06
28	277.84828333333333349992	276.51853333333333356658	-1.32974999999999993334	2014-12-02 03:00:00-06
29	280.29426666666666699998	279.05683333333333353332	-1.23743333333333346666	2014-12-02 04:00:00-06
30	330.54229999999999993341	329.03126666666666676676	-1.51103333333333316665	2014-12-02 05:00:00-06
31	434.11016666666666690003	432.71988333333333343333	-1.39028333333333346670	2014-12-02 06:00:00-06
32	452.75403333333333359993	461.50368333333333313330	8.74964999999999953337	2014-12-02 07:00:00-06
33	308.88524035087719299930000	381.97927368421052603329	73.09403333333333033360000	2014-12-02 08:00:00-06
34	161.13030000000000000001	341.19116666666666663328	180.06086666666666663327	2014-12-02 09:00:00-06
35	63.58358333333333329996	351.21714999999999996668	287.63356666666666666672	2014-12-02 10:00:00-06

SELECT sum(grid) as sum_grid, sum(use) as sum_use, sum(use) - sum(grid) as sum_gen, localhour FROM university.electricity_egauge_hours

WHERE (dataid IN (SELECT dataid FROM university.metadata WHERE program_energy_internet_demo = 'yes') and (localhour between '2014-12-01' and '2015-02-28'))

group by localhour

order by localhour

b. *Pecan Street Data Export to Microsoft Excel*

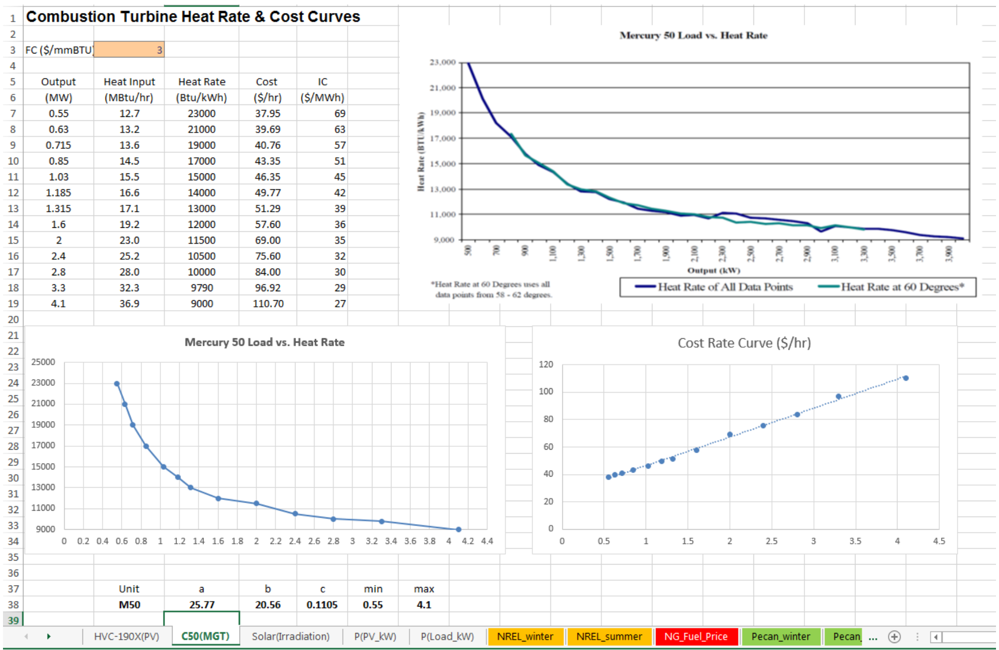
i. For the daily loads in summer, open the .xlsx-file **subquery_summer(sum)** in Directory **Part 1 - Data\Microgrid Load (Pecan Street)**

ii. ii. For the daily loads in winter, open the .xlsx-file **subquery_winter(sum)** in Directory **Part 1 - Data\Microgrid Load (Pecan Street)**

Remember: The residential load data for summer and winter was created as the mean over all hourly loads during the queried time span.

- **Microturbine Generation**

To model the generation cost curve for the Centaur 50 gas turbine as a quadratic function a similar heat rate curve in comparison to the Mercury 50 gas turbine was assumed. The cost function is plotted as illustrated in the writer **C50(MGT)** in the .xlsx-file **mueller_analysis** in **Directory Part 2 – Data Analysis\Microgrid (Mueller)**



Combustion Turbine Heat Rate & Cost Curves

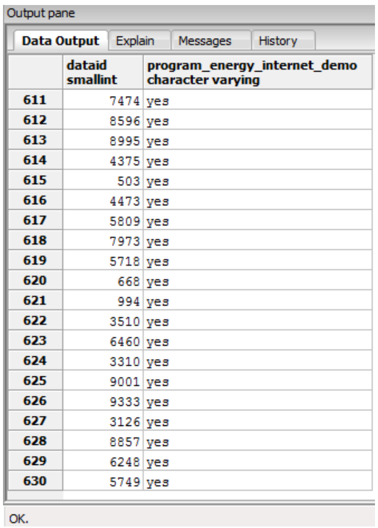
FC ($/mmBTU) 3

Output (MW)	Heat Input (MBtu/hr)	Heat Rate (Btu/kWh)	Cost ($/hr)	IC ($/MWh)
0.55	12.7	23000	37.95	69
0.63	13.2	21000	39.69	63
0.715	13.6	19000	40.76	57
0.85	14.5	17000	43.35	51
1.03	15.5	15000	46.35	45
1.185	16.6	14000	49.77	42
1.315	17.1	13000	51.29	39
1.6	19.2	12000	57.60	36
2	23.0	11500	69.00	35
2.4	25.2	10500	75.60	32
2.8	28.0	10000	84.00	30
3.3	32.3	9790	96.92	29
4.1	36.9	9000	110.70	27

Unit	a	b	c	min	max
M50	25.77	20.56	0.1105	0.55	4.1

- **PV Generation**

As shown by the data queries, as of April 2015, 630 single-family homes including 256 house equipped with roof-mounted PV systems at an average per-home size of 5.5 kWh (pv = 'yes') were selected for the Energy Demonstration Project (program_energy_internet_demo = 'yes').

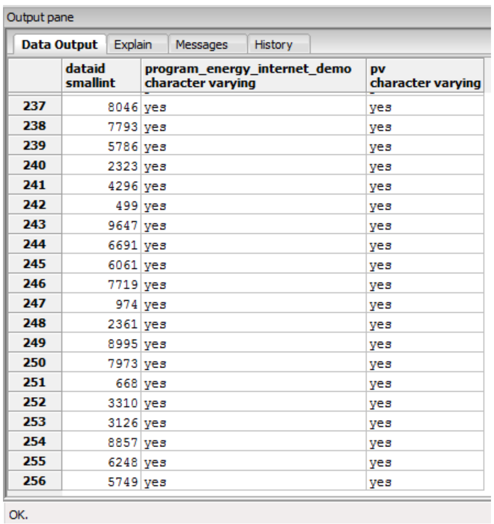


Output pane

Data Output | Explain | Messages | History

	dataid smallint	program_energy_internet_demo character varying
611	7474	yes
612	8596	yes
613	8995	yes
614	4375	yes
615	503	yes
616	4473	yes
617	5809	yes
618	7973	yes
619	5718	yes
620	668	yes
621	994	yes
622	3510	yes
623	6460	yes
624	3310	yes
625	9001	yes
626	9333	yes
627	3126	yes
628	8857	yes
629	6248	yes
630	5749	yes

OK.



Output pane

Data Output | Explain | Messages | History

	dataid smallint	program_energy_internet_demo character varying	pv character varying
237	8046	yes	yes
238	7793	yes	yes
239	5786	yes	yes
240	2323	yes	yes
241	4296	yes	yes
242	499	yes	yes
243	9647	yes	yes
244	6691	yes	yes
245	6061	yes	yes
246	7719	yes	yes
247	974	yes	yes
248	2361	yes	yes
249	8995	yes	yes
250	7973	yes	yes
251	668	yes	yes
252	3310	yes	yes
253	3126	yes	yes
254	8857	yes	yes
255	6248	yes	yes
256	5749	yes	yes

OK.

c. Solar Irradiation Data

The solar irradiation data was received from the National Solar Radiation Database of the National Renewable Energy Laboratory (NREL). Average solar irradiation data was queried for Austin, Texas for summer (Jun 1 - Aug 31, 2012) and winter (Dec 1, 2011 - Feb 28, 2012). The data can be downloaded from

https://mapsbeta.nrel.gov/nsrdb-viewer/#/?activeLayers=0&baseLayer=groad&mapCenter=30.300723217778742%2C-97.61850357055664&zoomLevel=12

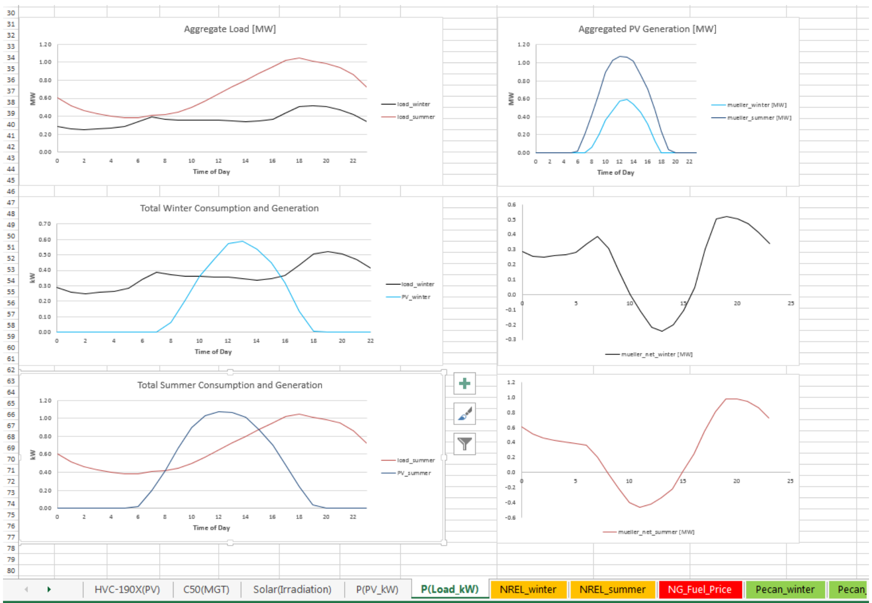
A backup can also be found in the Directory **Part 1- Data\Solar irradiation (NREL).**

d. Solar Irradiation Data Export to Microsoft Excel

The irradiation data is then exported to the **.xlsx-file mueller_analysis** in the Directory **Part 2 – Data Analysis\Microgrid (Mueller)** and plotted for summer and winter.

- **Net Renewable Electricity Usage and Storage Potential**

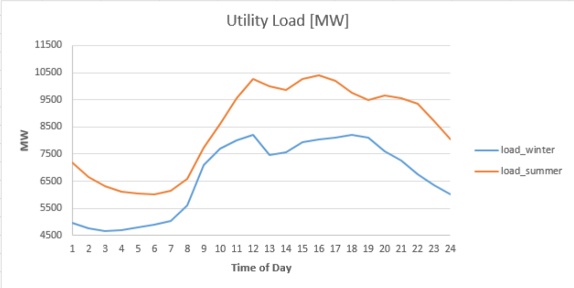
The net renewable electricity usage in the Mueller Community was generated by comparing the total demand from the residential loads with the potential PV generation during both summer and winter days. The plotted figures are generated by the data imports using Excel. The figures can be found under the writer **P(Load)** in the .xlsx-file **mueller_analysis** in the Directory **Part 2 - Data Analysis\Microgrid (Mueller)** plotted for summer and winter.



- **Utility Load**

The utility load was obtained for a the weekly load profile in Chang et al. [CCC90] and plotted for a single day period under the writer **Daily Load** in in the .xlsx-file **utility_analysis** in the Directory **Part 2 - Data Analysis\Utility (Taipower)**.

t	load_winter	load_summer
1	4950	7200
2	4750	6650
3	4650	6300
4	4700	6100
5	4800	6050
6	4900	6000
7	5050	6150
8	5600	6600
9	7100	7750
10	7700	8600
11	8000	9550
12	8200	10250
13	7450	10000
14	7550	9850
15	7950	10250
16	8050	10400
17	8100	10200
18	8200	9750
19	8100	9500
20	7600	9650
21	7250	9550
22	6750	9350
23	6350	8700
24	6000	8050
MAX	8200	10400
MIN	4650	6000



Daily Load | AGU (MW)

Part 2: Data Analysis

The generation profiles for the microgrid, utility and joint generation are plotted with Excel and can be found in the .xlsx-file **jointgen_analysis** under the Directory **Part 2 – Data Analysis\Joint Generation (Interconnection)**.

Microgrid generation without storage for summer and winter days (in MW)	**jointgen_analysis** **Spreadsheet: Microgrid**
Microturbine generation with storage during summer and winter days (in MW)	**jointgen_analysis** **Spreadsheet: Microgrid**
Storage output during summer and winter days (in MW)	**jointgen_analysis** **Spreadsheet: Microgrid**

Aggregated thermal generation for summer and winter days (in MW)	**jointgen_analysis** **Spreadsheet: Utility**

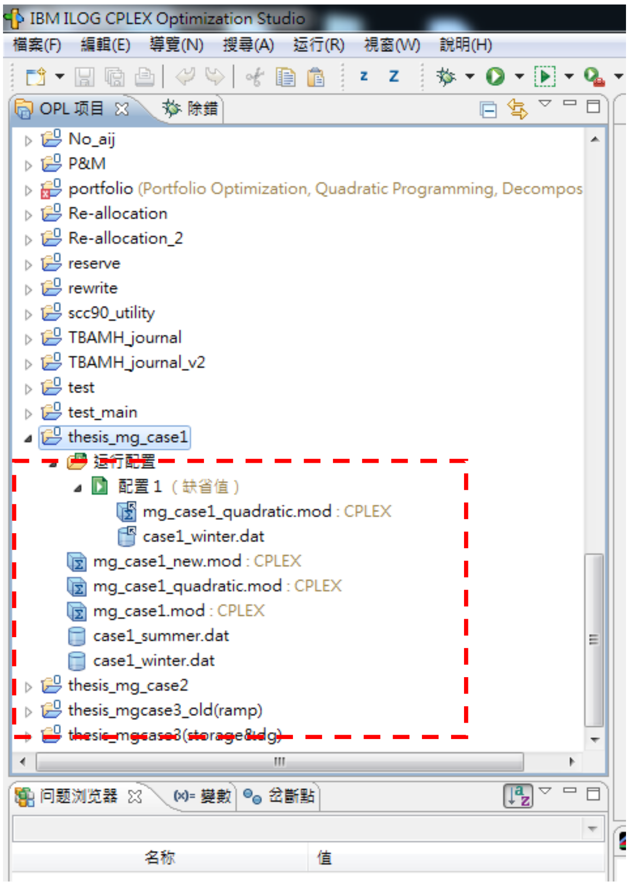
Joint generation without storage during summer days (in MW)	**jointgen_analysis** **Spreadsheet: Joint(no_storage)**
Joint generation without storage during winter days (in MW)	**jointgen_analysis** **Spreadsheet: Joint(no_storage)**
Joint generation with storage during summer and winter days (in MW)	**jointgen_analysis** **Spreadsheet: Joint(storage)**
Storage output during summer and winter days (in MW)	**jointgen_analysis** **Spreadsheet: Joint(storage)**

Generation scenarios between Taipower and the Mueller microgrid	**jointgen_analysis** **Spreadsheet: Coalition values**
Coalition values and cost savings for Taipower and the Mueller microgrid	**jointgen_analysis** **Spreadsheet: Shapley Value**

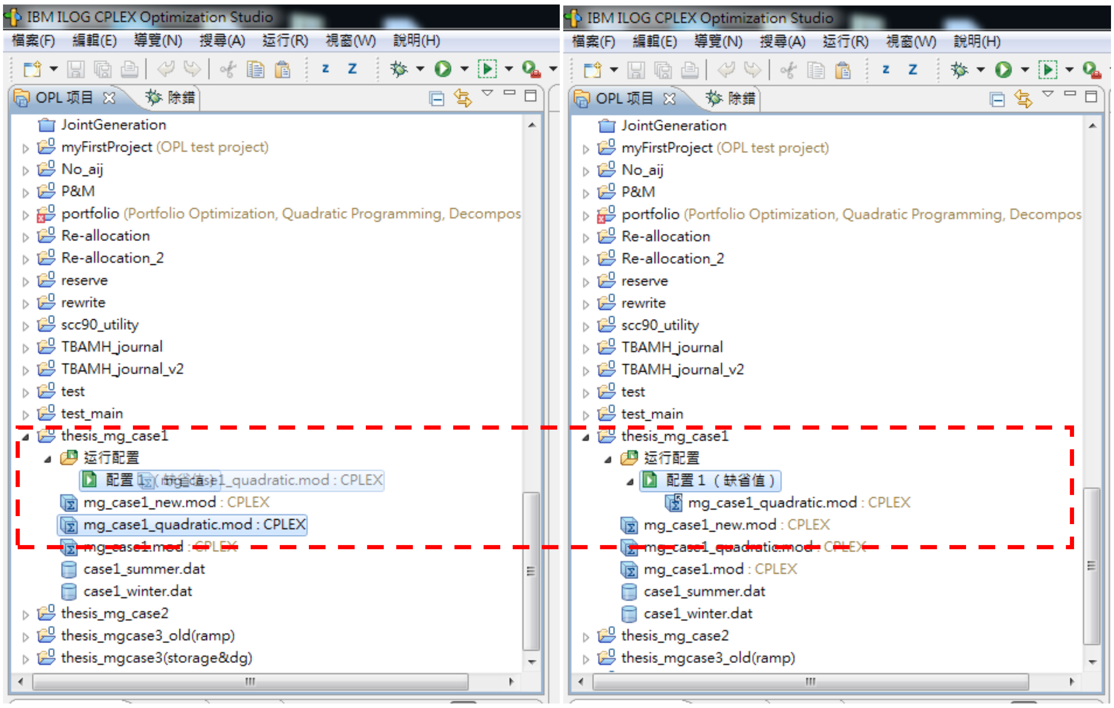
Part 3: Operations Research

Part 3.1: Microgrid Generation (No Storage) – CPLEX

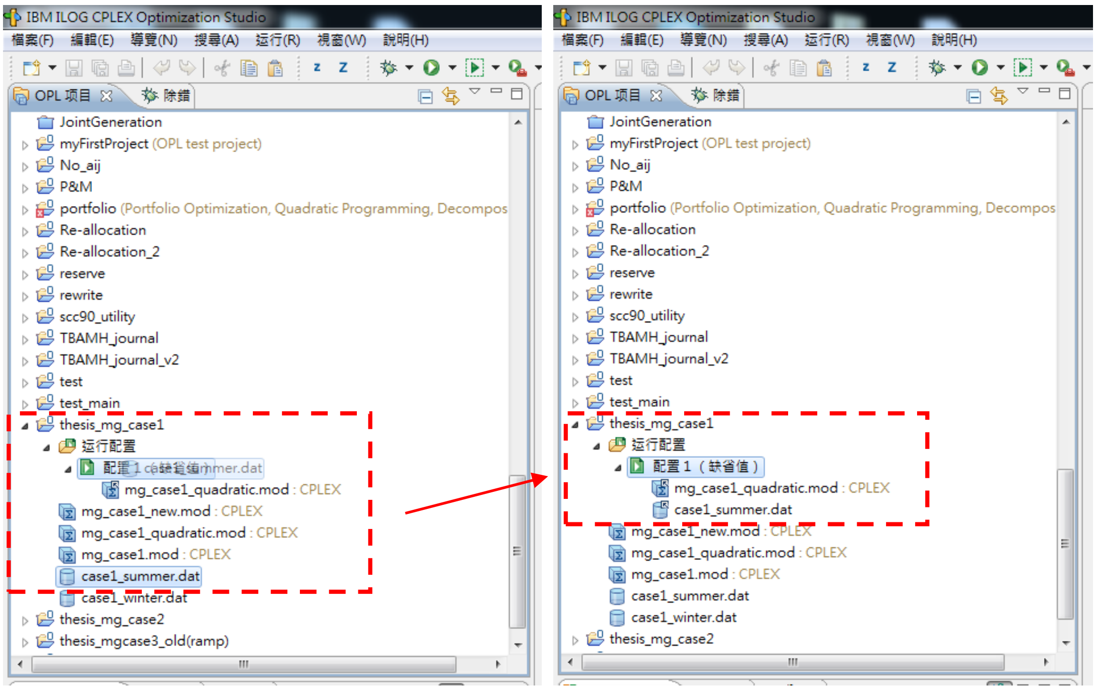
- Executive Software
  - ILOG CPLEX Studio IDE 12.2 @ HPZ400
- Code file in **Part 3 - Operations Research\thesis_mg_case1**
  - mg_case1_quadratic.mod
  - case1_summer.dat
  - case1_winter.dat
- Description: This optimization algorithm minimizes the standalone generation cost of the microgrid without storage for summer and winter.
- Steps
  - Step 1: Click the desktop "OPL IDE"
  - Step 2: Expand thesis_mg_case1 by left-click



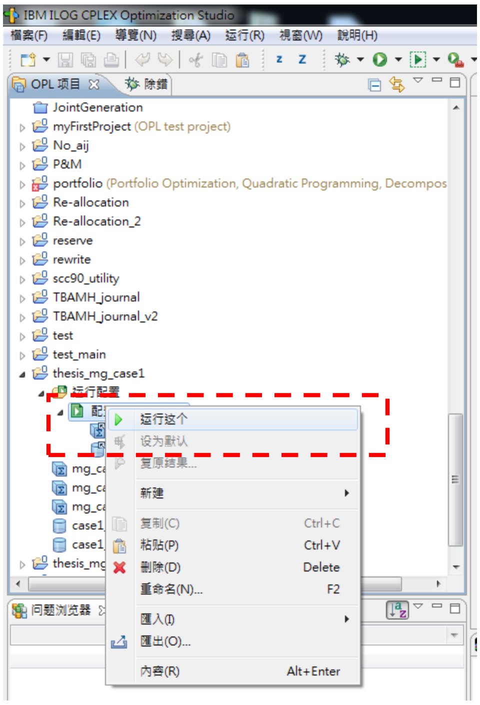
  - Step 3: Select the model file **mg_case1_quadratic.mod** and move it into the "Basic configuration" subfolder.



- Step 4: Select the respective data file for summer **case1_summer.dat** or winter **case1_winter.dat** and also move it into the "Basic configuration" subfolder.

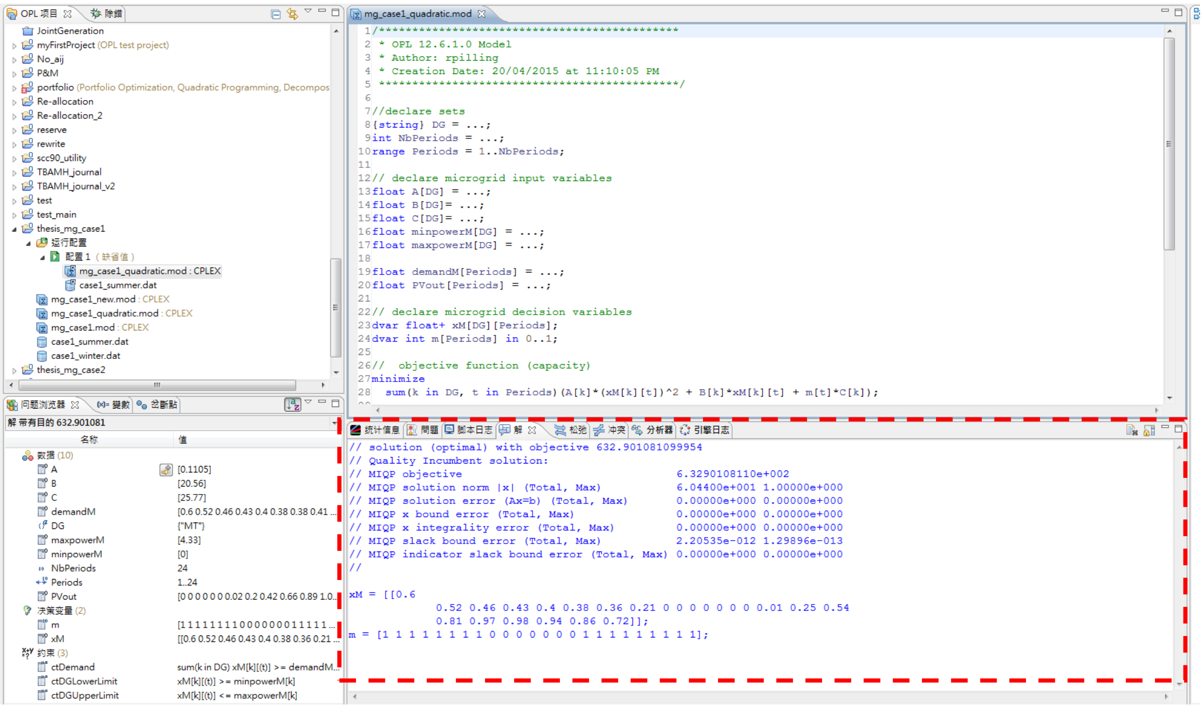


- Step 5: Execute the algorithm by right-click on the "Basic Configuration" and left-click on the appearing "Run"-Button

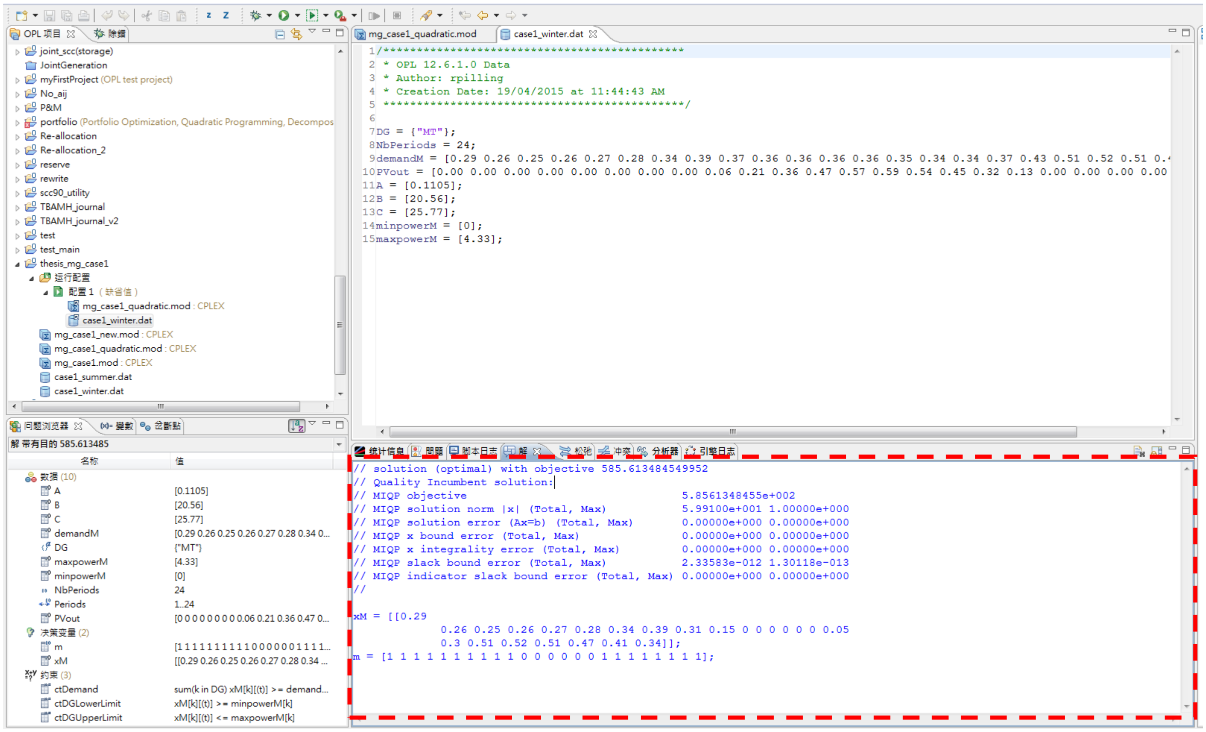


○ Step 6: In the "Script Log" to view the results of algorithm

case1_summer.dat

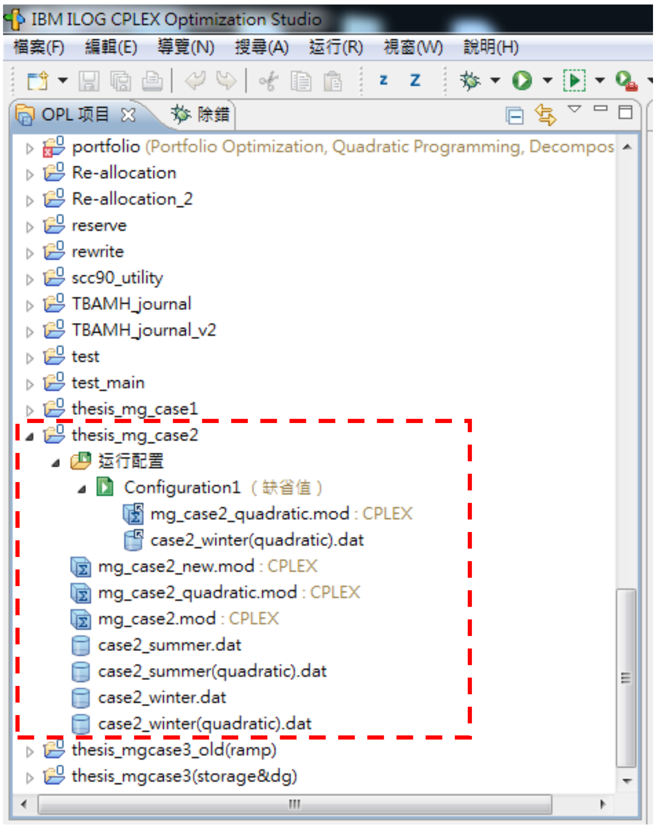


case1_winter.dat



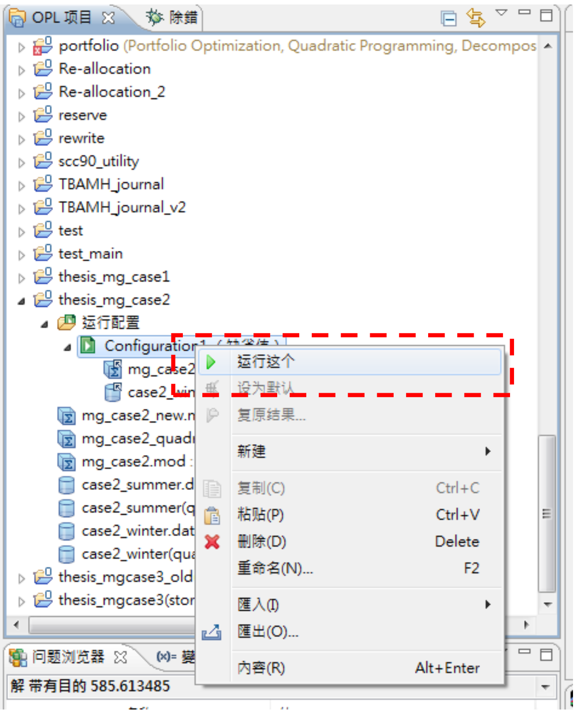
Part III.2: Microgrid Generation (Storage) – CPLEX

- Executive Software
  - ILOG CPLEX Studio IDE @ HPZ400
- Code file in **Part 3 - Operations Research\thesis_mg_case2**
  - mg_case2_quadratic.mod
  - case2_summer(quadratic).dat
  - case2_winter(quadratic).dat
- Description: This optimization algorithm minimizes the standalone generation cost of the microgrid with storage for summer and winter.
- Steps
  - Step 1: Click the desktop "OPL IDE"
  - Step 2: Expand thesis_mg_case2 by left-click



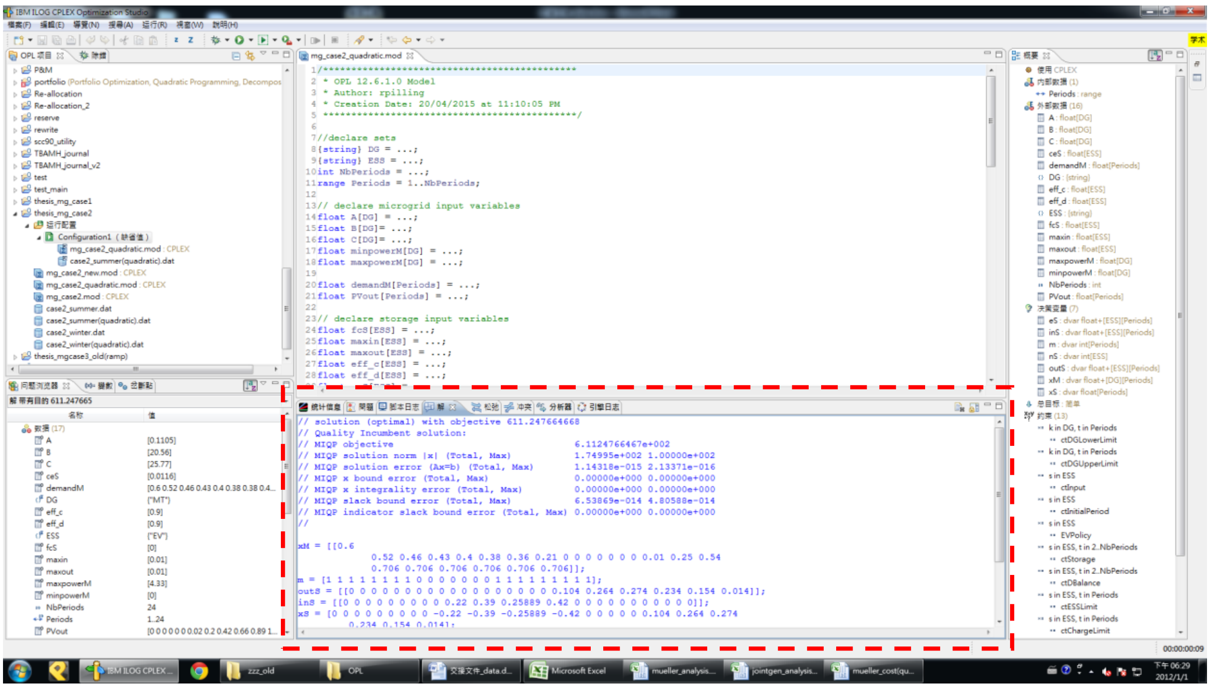
  - Step 3: Select the model file **mg_case2_quadratic.mod** and move it into the "Basic configuration" subfolder. *(compare with III.1)*
  - Step 4: Select the data file for summer **case2_summer(quadratic).dat** or winter **case2_winter(quadratic).dat** and also move it into the "Basic configuration" subfolder. *(compare with III.1)*

- Step 5: Execute the algorithm by right-click on the "Basic Configuration" and left-click on the appearing "Run"-Button

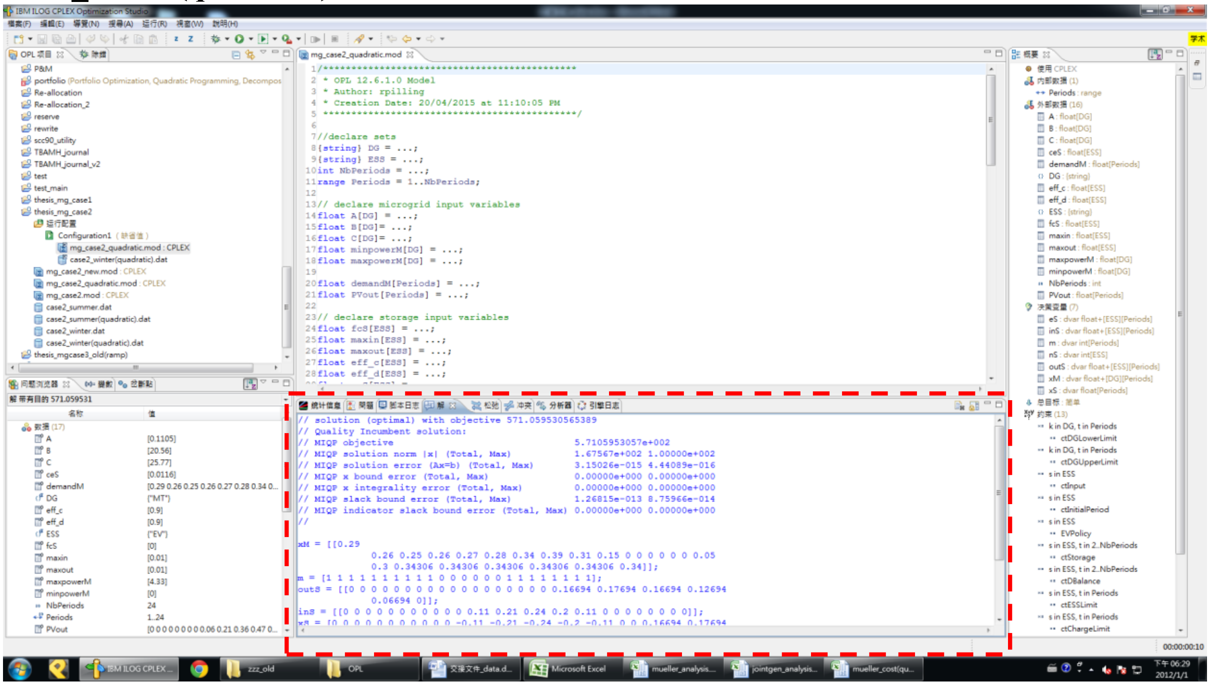


- Step 6: In the "Script Log" to view the results of algorithm

case2_summer(quadratic).dat

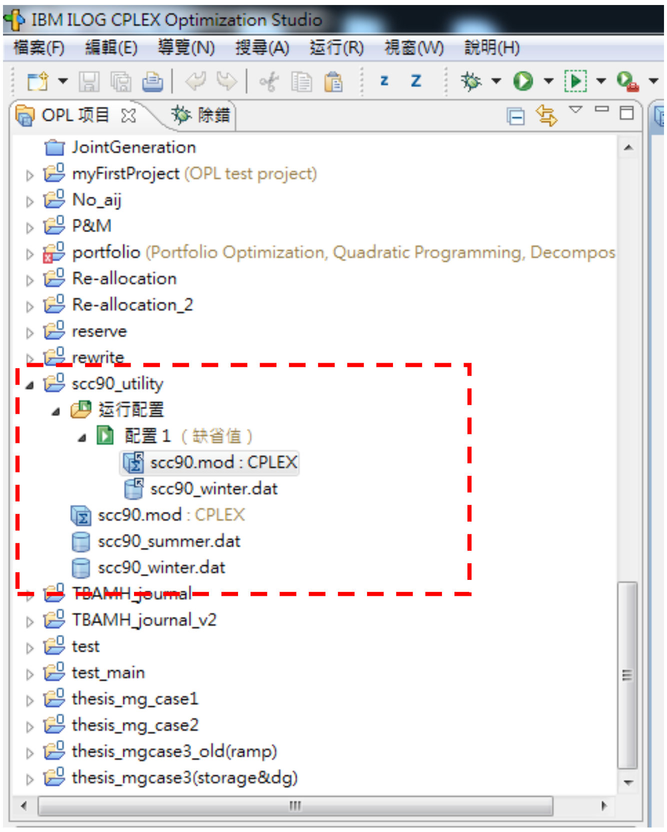


case2_winter(quadratic).dat



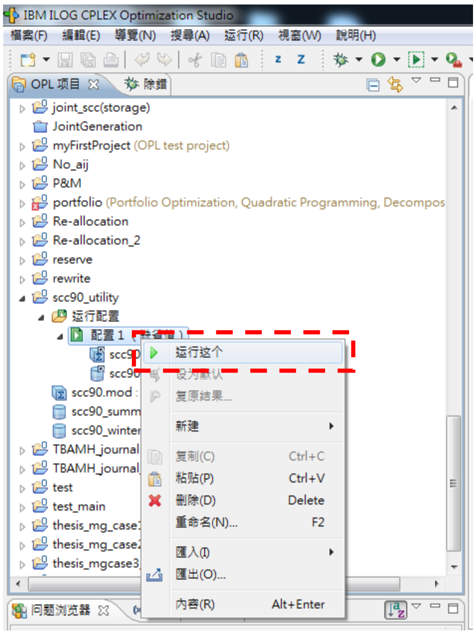
Part 3.3: Utility Generation – CPLEX

- Executive Software
  - ILOG CPLEX Studio IDE @ HPZ400
- Code file in **Part 3 - Operations Research\scc90_utility**
  - scc90.mod
  - scc90_summer.dat
  - scc90_winter.dat
- Description: This optimization algorithm minimizes the standalone generation cost of the utility for summer and winter.
- Steps
  - Step 1: Click the desktop "OPL IDE"
  - Step 2: Expand scc90_utility by left-click



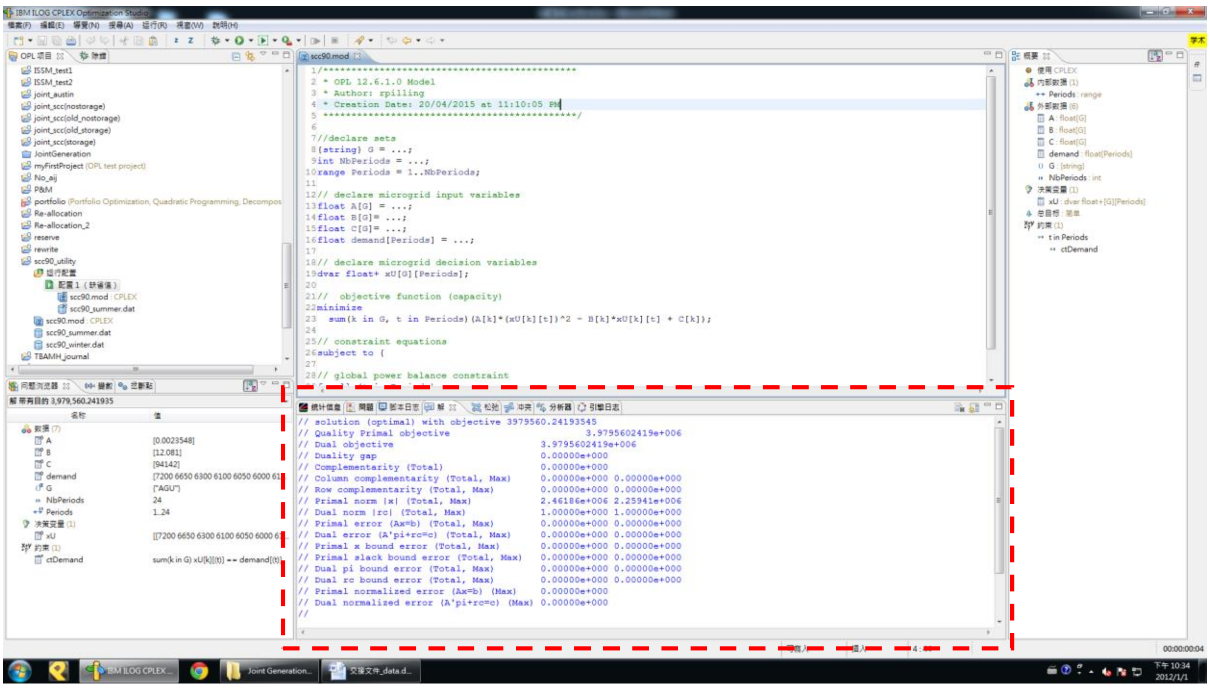
  - Step 3: Select the model file **scc90.mod** and move it into the "Basic configuration" subfolder. *(compare with III.1)*
  - Step 4: Select the data file for summer **scc90_summer.dat** or winter **scc90_winter.dat** and also move it into the "Basic configuration" subfolder. *(compare with III.1)*

- Step 5: Execute the algorithm by right-click on the "Basic Configuration" and left-click on the appearing "Run"-Button

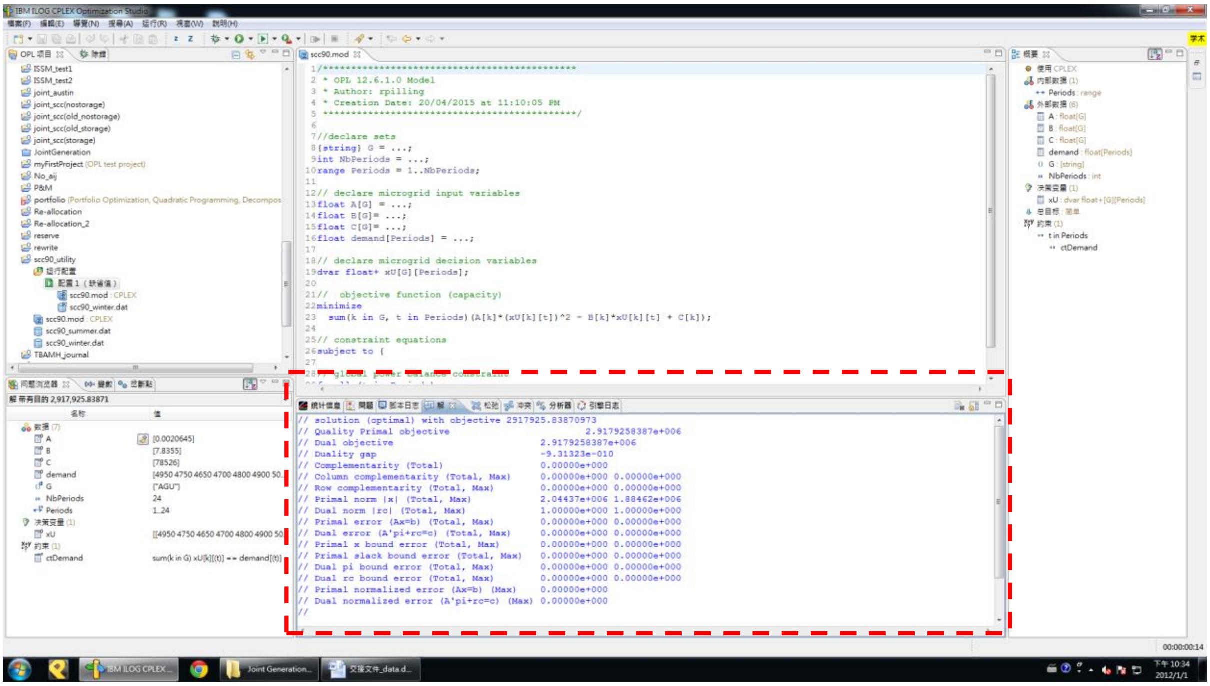


- Step 6: In the "Script Log" to view the results of algorithm

scc90_summer.dat

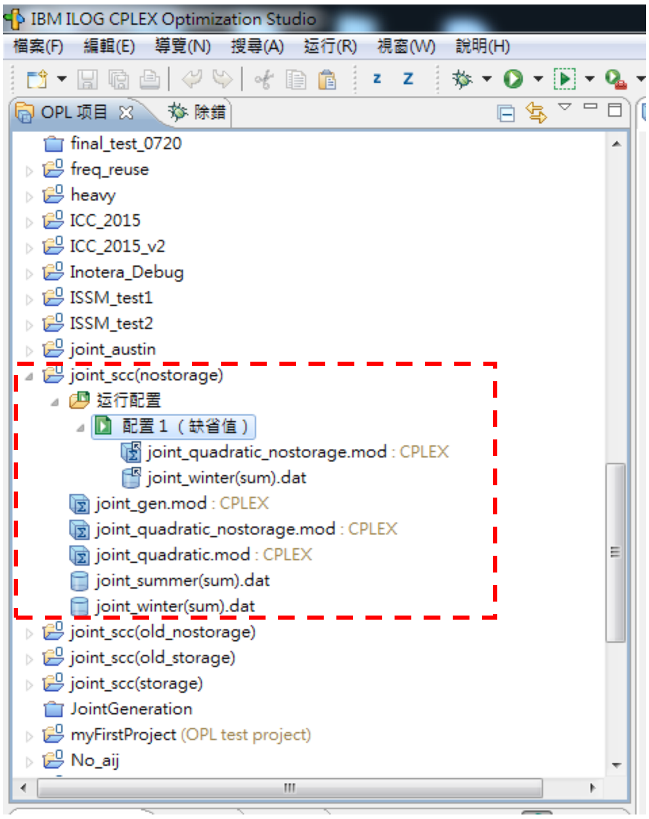


scc90_winter.dat



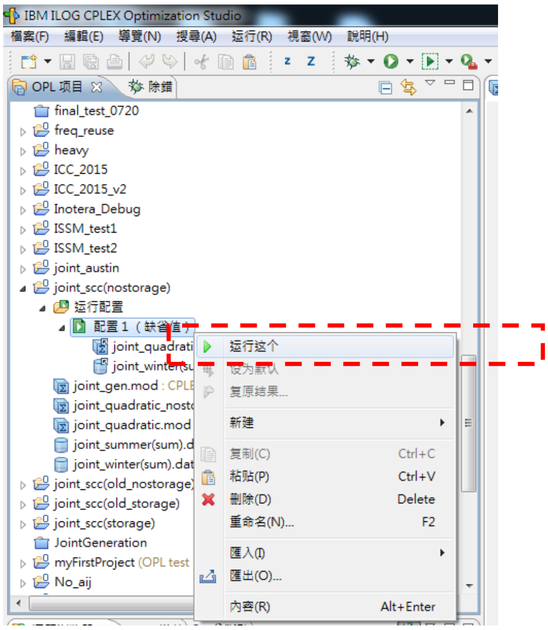
Part 3.4: Joint Generation (No Storage) – CPLEX

- Executive Software
  - ILOG CPLEX Studio IDE @ HPZ400
- Code file in **Part 3 - Operations Research\joint_scc(nostorage)**
  - joint_quadratic_nostorage.mod
  - joint_summer(sum).dat
  - joint_winter(sum).dat
- Description: This optimization algorithm minimizes the joint generation cost of the microgrid and the utility without storage for summer and winter.
- Steps
  - Step 1: Click the desktop "OPL IDE"
  - Step 2: Expand joint_scc(nostorage) by left-click



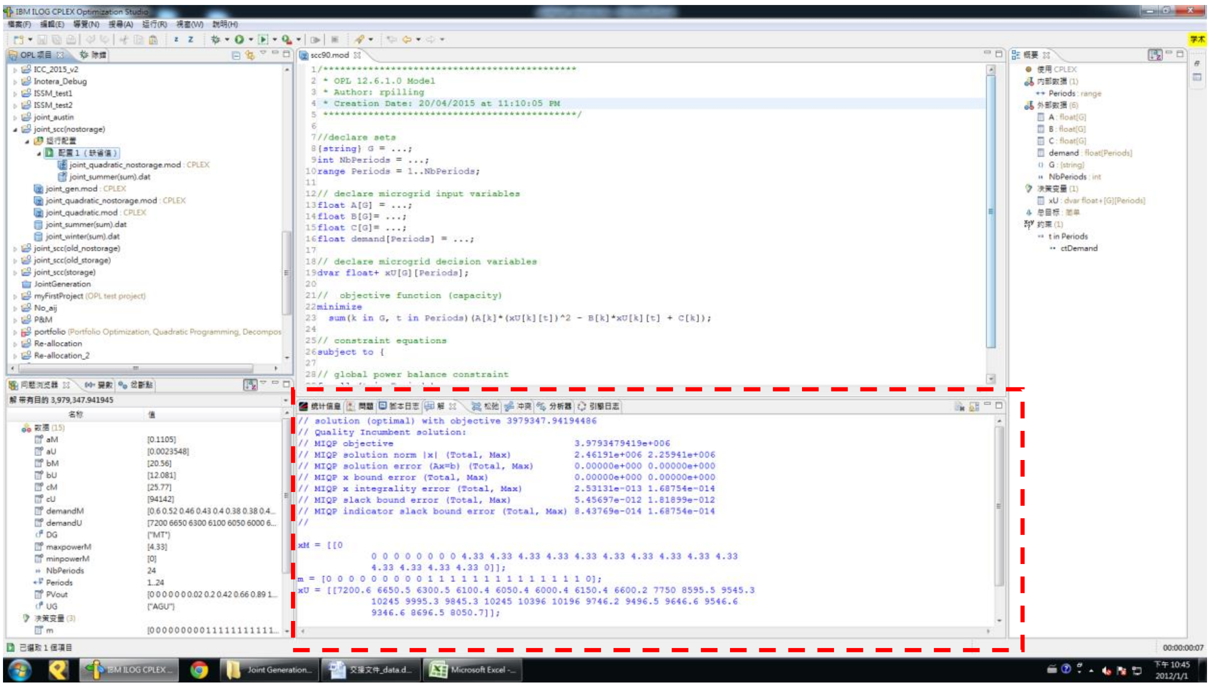
  - Step 3: Select the model file **joint_quadratic_nostorage.mod** and move it into the "Basic configuration" subfolder. *(compare with III.1)*
  - Step 4: Select the data file for summer **joint_summer(sum).dat** or winter **joint_winter(sum).dat** and also move it into the "Basic configuration" subfolder. *(compare with III.1)*

- Step 5: Execute the algorithm by right-click on the "Basic Configuration" and left-click on the appearing "Run"-Button

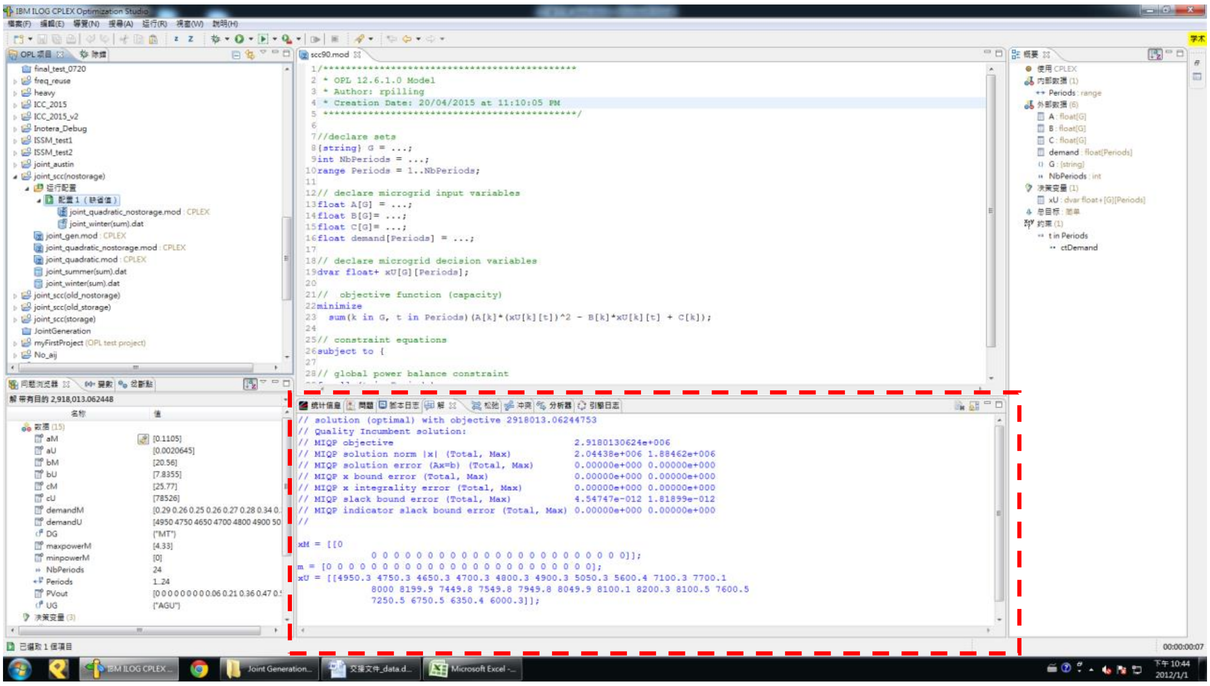


- Step 6: In the "Script Log" to view the results of algorithm

joint_summer(sum).dat

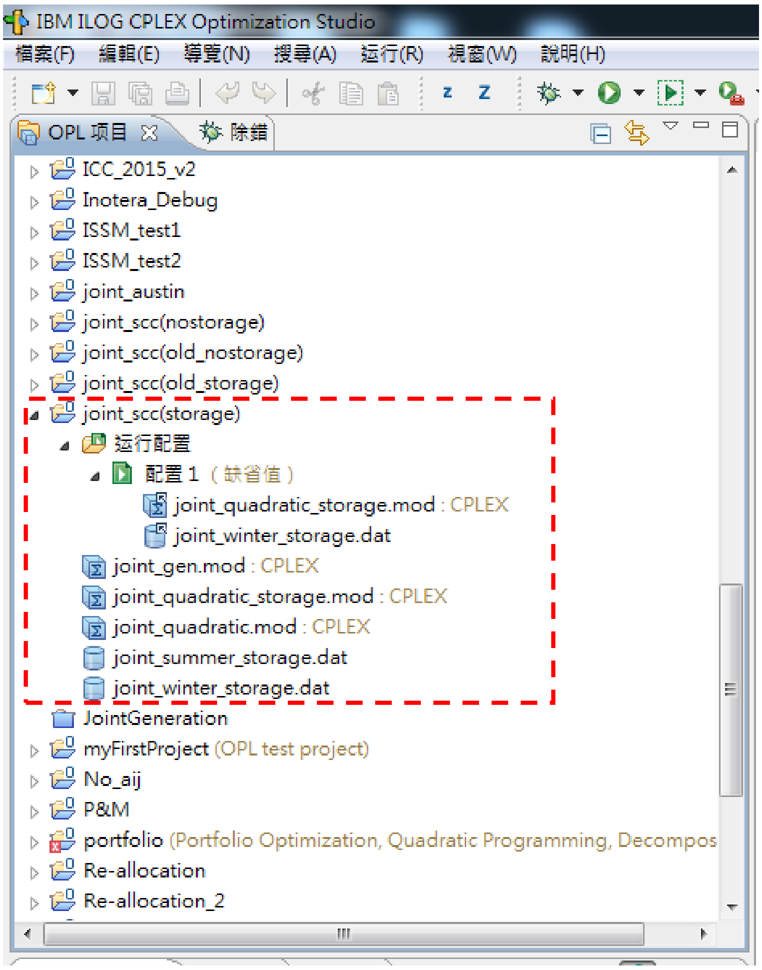


joint_winter(sum).dat



Part 3.5: Joint Generation (Storage) – CPLEX

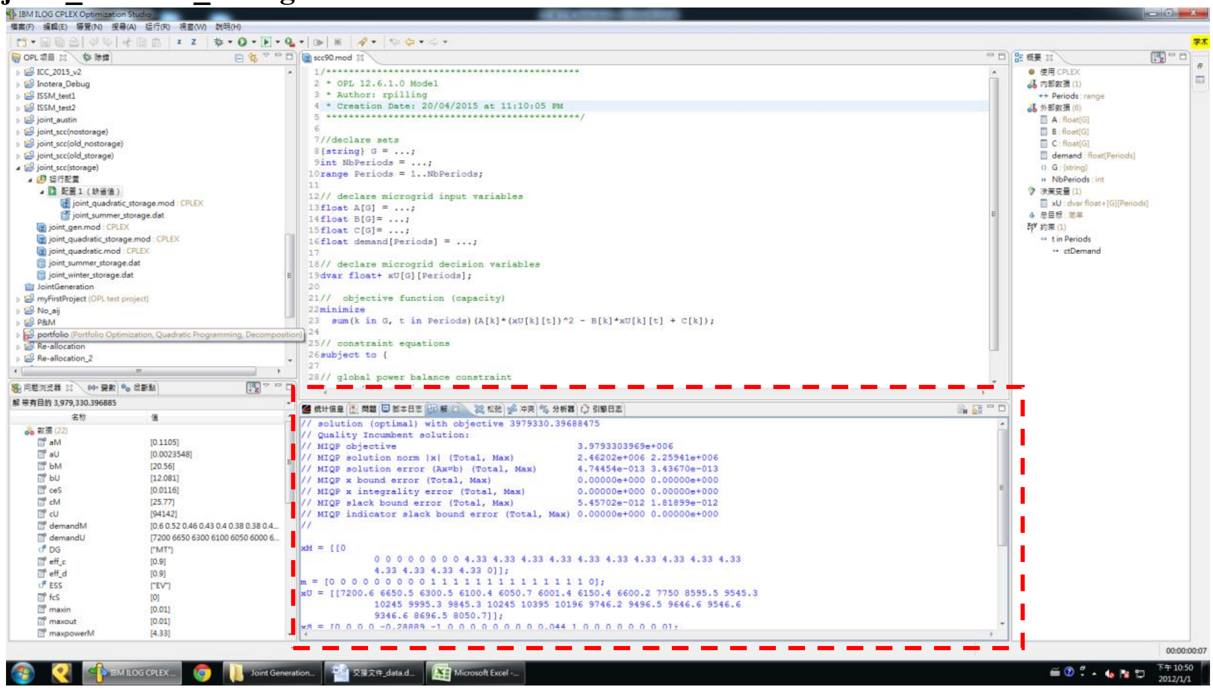
- Executive Software
    - ILOG CPLEX Studio IDE @ HPZ400
- Code file in **Part 3 - Operations Research\joint_scc(nostorage)**
    - joint_quadratic_storage.mod
    - joint_summer_storage.dat
    - joint_winter_storage.dat
- Description: This optimization algorithm minimizes the joint generation cost of the microgrid and the utility without storage for summer and winter.
- Steps
    - Step 1: Click the desktop "OPL IDE"
    - Step 2: Expand joint_scc(storage) by left-click



    - Step 3: Select the model file **joint_quadratic_nostorage.mod** and move it into the "Basic configuration" subfolder. *(compare with III.1)*

- Step 4: Select the data file for summer **joint_summer_storage.dat** or winter **joint_winter_storage.dat** and also move it into the "Basic configuration" subfolder. *(compare with III.1)*
- Step 5: Execute the algorithm by right-click on the "Basic Configuration" and left-click on the appearing "Run"-Button.
- Step 6: In the "Script Log" to view the results of algorithm

joint_summer_storage.dat



joint_winter_storage.dat