Optimal Dispatch of Heat and Power Producer in the Day-ahead Market

EA Energy Analysis Project

Course 42002

Modelling and Analysis of Sustainable Energy

System using Operations Research

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Contents

1 Introduction

In this project, a small utility is required to serve the heat load of a large industry. This portfolio is a combination of a 500MW wood-chips combined heat and power unit (CHP), a 350MW natural gas heat boiler, a 25000m^2 solar heating plant and a 4500MWh heat storage unit (See Figure 1). In addition, the small utility may also sell electricity in the market due to the electricity generation of CHP meanwhile.

The objective is to achieve optimal energy dispatch for each unit (i.e. heat production level), which places emphasis on combining copious systems scientifically to minimize the total cost to satisfy the heat demand.

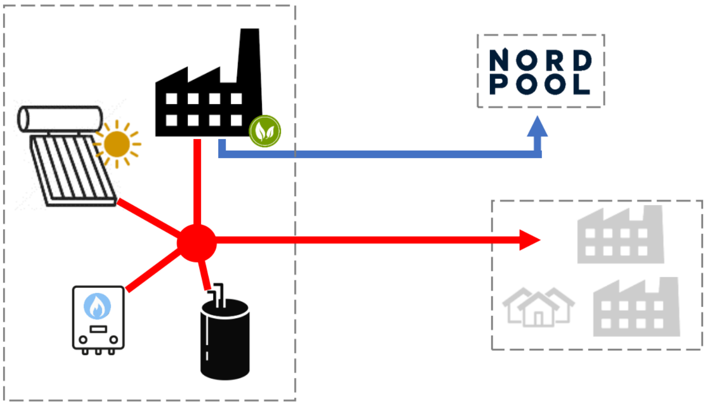


Figure 1: Sketch of the whole system

After implementing all the constraints, the mathematical model will be set up initially and afterwards it will be altered into codes of GAMS to attain optimal solution piecemeal.

(1) Basic level: Corresponding models of five scenarios are built on the same Unit Commitment model with importing different datasets (i.e. heat demand, power price and solar heat plant production). And the curves of all the units are inclined to reflect the optimal schedule.

(2) Superior level:

a) Taking weight coefficient of heat demand and power price into account, stochastic analysis is conducted across 5 scenarios.

b) Sensitivity analysis aims at selecting cardinal factor for optimal results. Power price and wood chip price have been analyzed separately.

2 Methodology

2.1 Isolated model in different units

2.1.1 Combined heat and power unit programming

The combined heat and power unit is aimed to generate electricity and produce heat simultaneously, which usually have a higher efficiency compared with the conventional unit.
In this project, assume the CHP unit as unit 1 (i=1). The cost of generating heat and power should be minimized to achieve optimal solution, while the benefit from electricity market should be maximized. For the cost part, the investment cost is neglect since these units are already set up. And the variable operation and maintenance cost is included ,while the fixed operation and maintenance cost is neglected because the model time period is one week.
In this case, the mathematical model can be built as following. The variable ”p” means the production level of heat supplied to the load, and the overall explanations of all abbreviations are shown in Appendix B table 4.

$$z_i = \sum_{t=1}^{T}\left(\frac{p(i,t)*om(i)}{chp\_eheat} + \frac{wc*p(i,t)}{chp\_eheat} + v(i,t)*su(i)*chp\_feed\right) \tag{2.1}$$

$$b = \sum_{t=1}^{T} p(i,t)*ratio*elec(t) \tag{2.2}$$

Also, constraints should be set up, including the minimum and maximum production level of heat and generation level of electricity, the relationship between on-line state and the start-up. Also, the production and generation levels should be positive, and on-line state and the start-up are set to be binary. The ramp rate and heat demand should also be considered. In this case, the constraints are as following.

$$\begin{cases} hmin(i)u(i,t) \le p(i,t) \le hmax(i)u(i,t) \\ p(i,t) \ge 0 \\ u(i,t), v(i,t) \in \{0,1\} \\ u(i,t) - u(i,t-1) \le v(i,t) \\ p(i,t) - p(i,t-1) \le r(i)*hmax(i) \end{cases} \tag{2.3}$$

The values of parameters are shown in the table below.

Table 1: Main parameters for CHP unit programming

Parameters	Values
Feed(MW)	500
Heat efficiency,name plate	84.58%
Electricity efficiency, net, name plate	28.89%
Minimal heat production level (MW)	15%*heat efficiency*feed=63.435
Maximal heat production level (MW)	Heat efficiency*feed=422.90
O&M cost(Euro per MW)	1
Start-up cost(Euro per MW)	80
Price of wood chips(Euro per MWh)	34.352
Ramp rate	0.85

The feed level is given in this case. And the values of heat efficiency, electricity efficiency and the operation and maintenance cost come from the technology data for energy plants-generation of Danish Energy Agency[1]. The minimal load percentage is normally set to 15%, according to the report[2], which shows that Danish CHP plants can have minimum loads in the range 10-20%. The start-up cost is suggested by the relative reference[3], which mentions 80 /MW for the start-up of a coal fired power plant, and it's very similar for the biomass CHP. The price of wood chip is according to Forest Fuels database[4]. And the ramp rate is estimated based on Wartsila product[5].

2.1.2 Natural gas heat boiler unit programming

Natural gas heat boiler in this case produce only heat, so the optimal schedule should minimize the cost for heat production. The unit model can be regarded as a unit commitment model, which is similar to the CHP. So the total cost of the natural gas boiler can be defined as follows:

$$z_i = \sum_{t=1}^{T} \left(\frac{p(i,t) * om(i)}{ng\_eheat} + \frac{ng * p(i,t)}{ng\_eheat} + v(i,t) * su(i) * ng\_feed \right) \tag{2.4}$$

And the constraints of the natural boiler are as follows, for whose consideration is similar to the CHP. In this case, $i = 2$.

$$\begin{cases} hmin(i)u(i,t) \leq p(i,t) \leq hmax(i)u(i,t) \\ p(i,t) \geq 0 \\ u(i,t), v(i,t) \in \{0,1\} \\ u(i,t) - u(i,t-1) \leq v(i,t) \\ p(i,t) - p(i,t-1) \leq r(i) * hmax(i) \end{cases} \tag{2.5}$$

The set of parameters are shown in the table below:

Table 2: Main parameters for natural gas heat boiler unit programming

Parameters	Values
Feed(MW)	350
Heat efficiency,name plate (%)	105
Minimal heat production level (MW)	15%*heat efficiency*feed=54.075
Maximal heat production level (MW)	heat efficiency*feed=360.5
O&M cost(Euro per MW)	1.1
Start-up cost(Euro per MW)	0
Price of natural gas(Euro per MWh)	37
Ramp rate	0.9

The feed level is given and the values of heat efficiency minimal load percentage and the operation and maintenance cost come from Danish Energy Agency. The start-up cost of natural gas heat boiler is normally considered as 0. The price of natural gas is chosen from Eurostas[6]. And the ramp rate is also estimated based on Wartsila product.

2.1.3 Solar heating plant unit programming

According to the study of solar energy, the OM cost of the solar energy is too small to be considered in a limited time period such as one week (i.e. 7*24 hours). So the OM cost of the solar energy can be assumed as zero. Also, solar resource is totally free,if the investment cost is excluded (i.e. initial capital). So the fuel cost will be zero, and this unit should be in on-line state primarily. Besides, the heat production levels of solar power are usually predicted, so day-ahead productions are set as parameters instead of variables used in this case to meet the heat demand. These values have been provided by the project.

$$z_i = \sum_{t=1}^{T} 0 \tag{2.6}$$

$$Total\ solar\ production = \sum_{t=1}^{T} solar(t) \tag{2.7}$$

2.1.4 Heat storage unit programming

The O&M and start-up cost of the heat storage is zero[1]. And the investment cost and fix O&M cost is excluded. Consequently, the cost of heat storage is set to zero.

$$z_i = \sum_{t=1}^{T} 0 \tag{2.8}$$

The constrains about heat storage include the minimal and maximal values of discharge, charge and storage volume, and the relationship between them. P(i,t) is the heat discharge level with u controlling the online status, and y(i,t) represents the open status of heat charge. Other constraints are similar to CHP unit. And the constraints are showed below.

$$\begin{cases} hmin(i) * u(i,t) \leq p(i,t) \leq hmax(i) * u(i,t) \\ hs\_mincha * y(i,t) \leq hs\_cha(i,t) \leq hs\_maxcha * y(i,t) \\ hs\_minsto \leq hs\_sto(i,t) \leq hs\_maxsto \\ hs\_sto(i,t) = hs\_sto(i,t-1) + hs\_cha(i,t) * hs\_e - p(i,t)/hs\_e \\ p(i,t) \geq 0 \\ u(i,t), y(i,t) \in \{0,1\} \\ u(i,t) - u(i,t-1) \leq v(i,t) \\ p(i,t) - p(i,t-1) \leq r(i) * hmax(i) \end{cases} \tag{2.9}$$

The set of parameters are shown in the table below:

Table 3: Main parameters for heat storage unit programming

parameters	values
minimal charge level (MW)	10
maximal charge level (MW)	400
minimal storage level (MW)	800
maximal storage level (MW)	4500
minimal heat production level (MW)	50
maximal heat production level (MW)	500
Heat efficiency	95%
O&M cost(Euro per MW)	0
ramp rate	1

The data sheet from Danish Energy Agency for Large-scale Hot Water Tanks only includes the O&M cost and heat efficiency. Other parameters are assumed referring to data of hydro-power reservoir[7].

2.2 Model integration

2.2.1 Mathematical model integration

The general objective of this project is to find the optimal dispatch strategy, which means the optimal solution of production levels for four units. The model integration mainly consists two parts, one is the final objective function, which aims to minimize the total cost considering the benefit from electricity market; the other is the total heat demand, which should be meet by the total heat production. In addition, for the heat storage unit both charge and discharge level should be considered in the demand equation to make it balanced. The objective function and the demand constraint can be deduced as follows:

$$MIN: \ Z_{total} = \sum_{i=1}^{I} z_i - b \tag{2.10}$$

$$\sum_{i}^{I} p(i,t) - hs\_cha('storage',t) + solar(t) = d(t) \tag{2.11}$$

2.2.2 Integration into GAMS

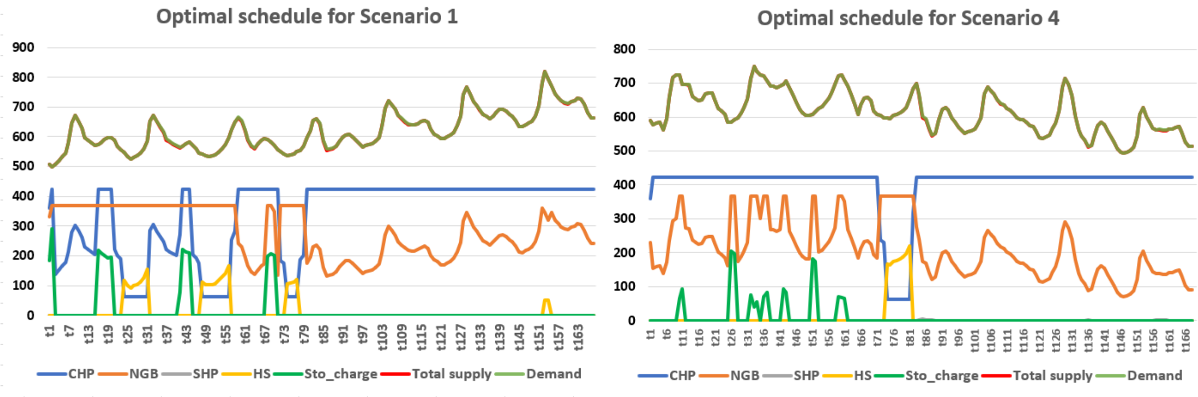
Based on mathematical model, the GAMS program is developed from basic Economic Dispatch to complete Unit Commitment model. (See Appendix A) The UC model is applied to CHP, Natural gas heat boiler and Heat storage considering fuel prices, variable O&M, start-up cost, max&minimum load and ramping constraints. Due to the one-week time horizon for this project, the investment cost and fix O&M cost are excluded. For Solar Heat Plant, it's assumed to have perfect knowledge to obtain the predicting production level thereby it's subtracted from heat demand directly. Power prices profiles in the day ahead market are from Energinet's Market data for DK1 and heat demand profiles are from Affaldvarme Aarhus.

The model is defined as MIP(mixed integer programming) problem since the available data is the discrete hourly variables which are integer values between their bounds[8]. Therefore, the resolution of results is also hourly. Last but not least, the basic principle of implementing coding is easy to adjust the magnitude of basic parameters for further analysis, which serves the convenience of the project's commissioner as far as possible.

3 Results

3.1 Operation Schedule Analysis

After solving the unit commitment model using MIP, the optimal schedule of this portfolio is obtained for five scenarios. Taking Scenario 1&4 for an example, the heat production level chart is showed below including the four unit, total supply and demand curves.(See Appendix B Figure xx-xx for other scenarios and Table xx-xx for detailed date)



**CHP, NGB, SHP, HS are short for four units respectively.*

Figure 2: Optimal schedule for Scenario 1&4

When comparing the results of different scenarios, it's obtained that the total supply and demand curves are identical, which means the fundamental heat demand is met by the schedule. In general, CHP unit usually is operated on high generating level to serve basic demand and Natural gas boiler (NGB) is to serve the peak demand with fluctuating production level following the demand curve. This is due to the fuel price and OM cost for CHP is lower. Besides,for the profits of selling electricity, from Figure 3, the highest benefit level is connected to the lowest total cost, which implies that the electricity crediting to the grid plays a crucial role to decrease the average cost per MW heat production. As to solar heat plant(SHP), its predicting heat supply is always below 5 MW based on previous data which is relatively negligible to total demand. The heat storage unit (HS) provides flexibility to the whole system. HS usually discharges heat when the CHP production is really low to meet the demand with NGB and is on charge status accompanying with high production level of both CHP and NGB. This could avoid striking production change and protect the facilities with demand satisfied. Basically, the portfolio of four units reaches the stable production status from the middle of one week.

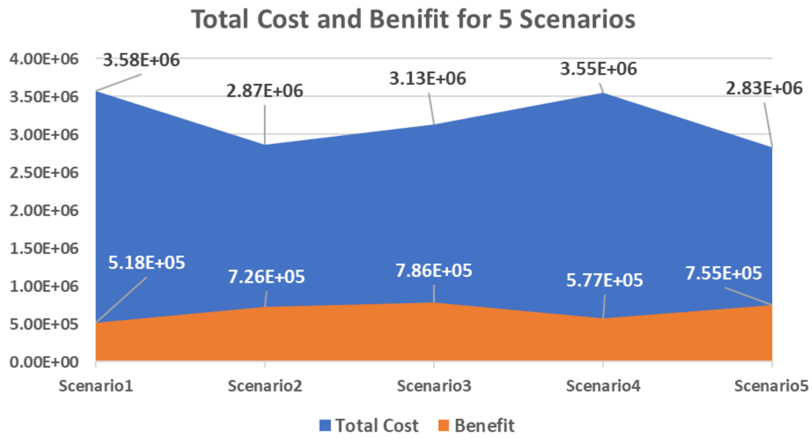


Figure 3: Total Cost and Benefit for 5 Scenarios

For Figure 4, the weighted demand and power price are calculated by multiplying the weight (Probability) and summing across the scenarios. The NGB production is changing with the demand variation, especially during the peak period on the weekend. It could be deduced that there is a positive correlation between CHP production and power price. And CHP often operates at the maximum level in stable status. The special case is Scenario 5, where the NGB is closed for 6 hours and CHP is closed for the last hours with significant increase of NGB & HS generation. This is partly on account of the markedly power price surge on the first two days and thus store certain amount of heat to replace the CHP at the last hour with low power price. However, if we extend the time horizon rather than only one week, the enormous start-up cost of CHP must be considered that would change the results.

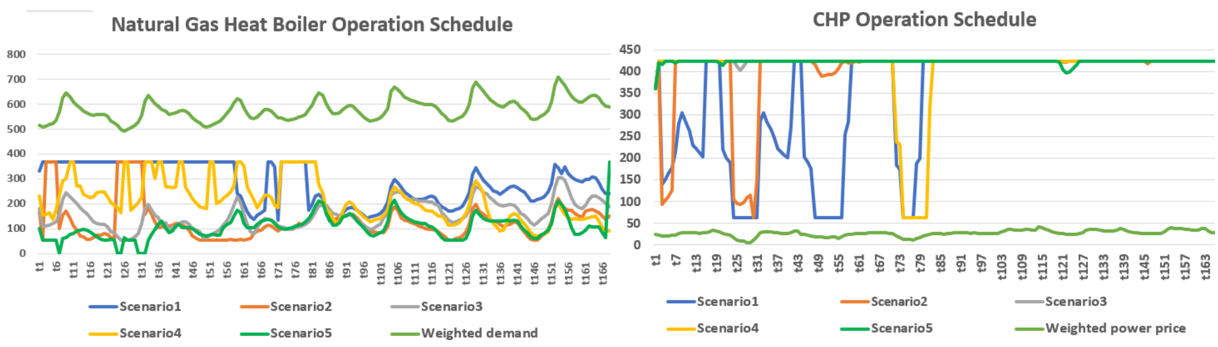


Figure 4: NGB & CHP Operation Schedule

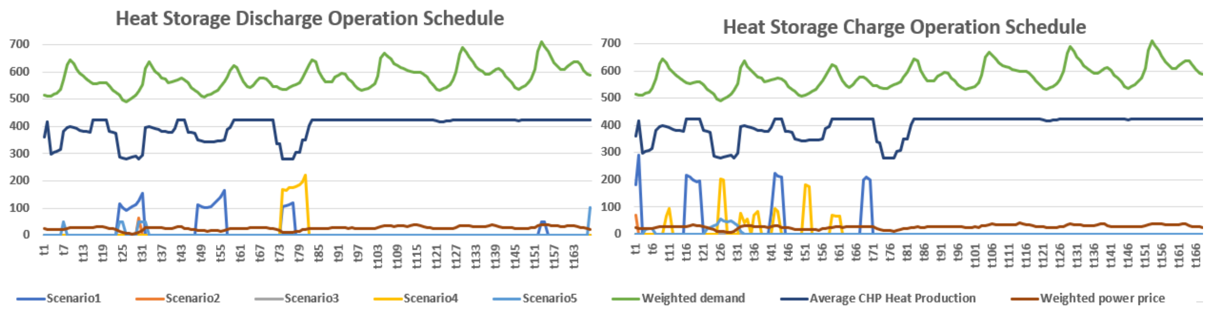


Figure 5: Hear Storage Operation Schedule (Discharge & Charge)

3.2 Shadow Value of the Constraints

The shadow value of the constraint is the change of optimal objective function value cost if the constraint is relaxed by one unit. Therefore, the shadow value of heat demand constraints, which means the increase of total cost with one unit increase of demand, is exactly the reference price of heat sold to the customers. Take Scenario 1 for a instance(See Figure xx), the shadow value ranges from 36.29 to 40.22 and stabilizes at 36.29 finally. The shadow value can be thereby applied to heat pricing. Furthermore, the stable shadow value reflects the feasibility and robustness of this portfolio to serve the heat load. In this project, other constraints do have shadow values, too. However, the realistic meaning of those are not prominent.

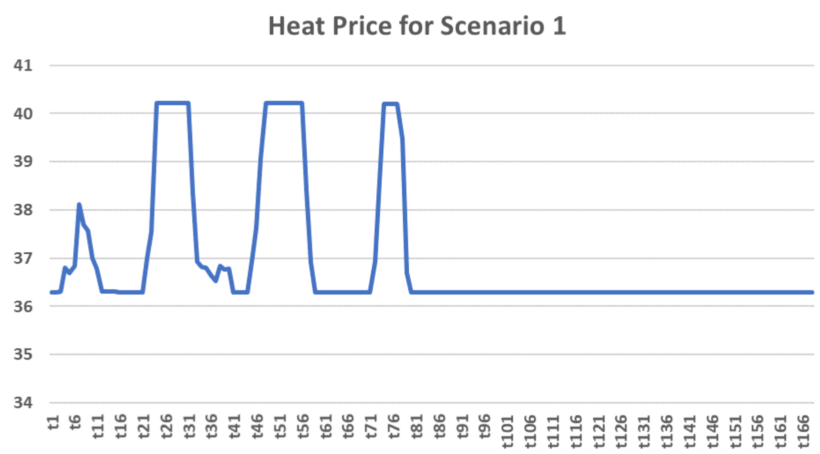


Figure 6: Hear Price for Scenario 1

4 Interpretation

4.1 Stochasticity Analysis

The purpose of the stochasticity analysis is to make scenarios with different probability "coexist", which optimizes the model by considering several possible scenarios and attributing them according to the weight. To meet the target, a new set "S" including different scenarios for electricity price and heat demand has been added in the model. And to simplified the problem, only Scenario 1 has been adjusted in this way to make comparison.

4.1.1 Stochasticity Analysis on electricity prices

The general mathematical model alters slightly from the previous one due to the combination of different scenarios with the final objective function showen below.

$$MIN : Z_{total} = \sum_{i=1}^{I} z_i - \sum_{t=1}^{T}\sum_{s=1}^{S} scen\_p(s) * p(i,t) * ratio * elec(t,s) \tag{4.1}$$

Then a GAMS model can be built to abtain the optimal solution. According to the GMAS result (see Figure 7), the heat production level in the front half of the time period has changed a lot while the latter half almost stay the same as the original heat production in scenario 1. In the front part, CHP heat production level has became more stable and higher than the one without stochasticity analysis, while for the natural gas heat boiler, production level has been more fluctuate compared to the original one. In addition, in the stochasticity case, the heat storage almost doesn't operate in the whole period.

4.1.2 Stochasticity Analysis on heat demand

Adding the stochasticity analysis of heat demand in the model makes change to the demand constraint part. So the constraint can be adjusted as below.

$$\sum_{s=1}^{S} scen\_d(s) * d(t,s) = \sum_{i}^{I} p(i,t) - hs\_cha('storage',t) + solar(t) \tag{4.2}$$

After applying the model into GAMS as well, the GAMS result in Figure 8 shows the influence of stochasticity on heat demand. Production level of CHP unit only change slightly in this case, with significant fluctuation in the front part and maximization level in the latter part. Speaking of the natural gas heat boiler, it has a similar production level with the original scenario in the front half, and it begins to increase proportionally also with a growing proportion in the latter part in general. For the heat storage unit, the level has decreased a little.

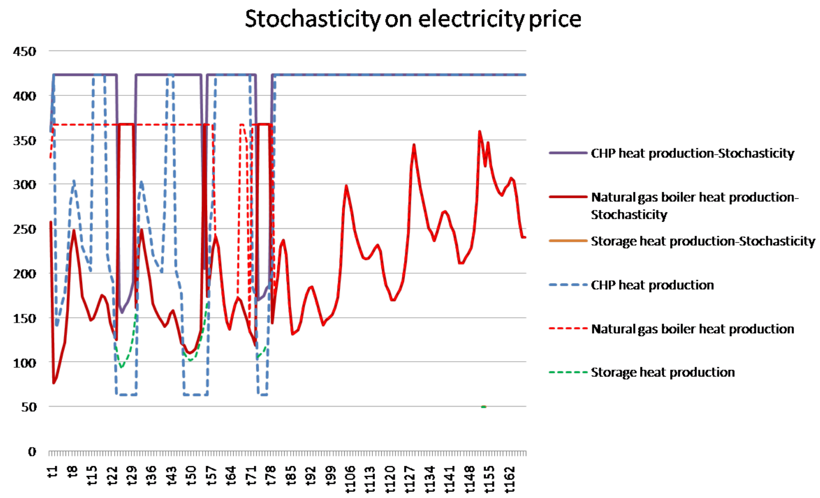


Figure 7: Stochasticity on electricity price

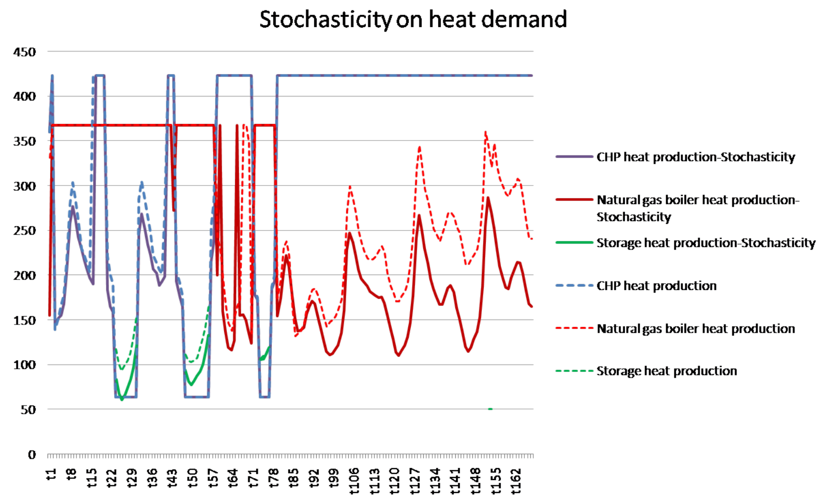


Figure 8: Stochasticity on heat demand

4.2 Sensitivity analysis

4.2.1 Statement of sensitivity analysis

Usually, the sensitivity analysis is to determine the key factor which has a bigger influence than others through setting the same variation range to each factor and observing the final result of the objective function. Getting the key factors will greatly benefit decision-making significantly or do precaution for variation of central factors.

The factors for sensitivity analysis should have uncertainty in themselves otherwise the analysis will be useless. Therefore, here the factors chosen for the sensitivity analysis are the electricity price which is associated with the electricity production, and the price of wood chips which influence heat production profoundly. And the same variation range will be set to 0%, $\pm 10\%$,$\pm 20\%$,$\pm 30\%$,$\pm 40\%$,$\pm 50\%$. The test method intends to vary the factors within same range and observe the gradient generated by the variation.

Though there is negative electricity price in the $scenario_1$, which could occur in reality, this part will only focus on the scenario 2 that's prior to be considered as a high probability event.

4.2.2 The result of sensitivity analysis and comments

In order to facilitate the display of results, they will be shown as the variational percentage of the original $scenario_2$ objective function (Eq.2.6), which follows the equation:

$$result = \frac{Z_{new,s=2} - Z_{total,s=2}}{Z_{total,s=2}} \times 100\% \tag{4.3}$$

Before displaying the results, something needs to be mentioned: If the result is positive that turns out to be unexpected, the total cost of $scenario_2$ after sensitive variation is higher than the original one. As for the negative result, the situation will be diametrically opposed.

Then the sensitivity analysis of the electricity price and wood chips are shown respectively:

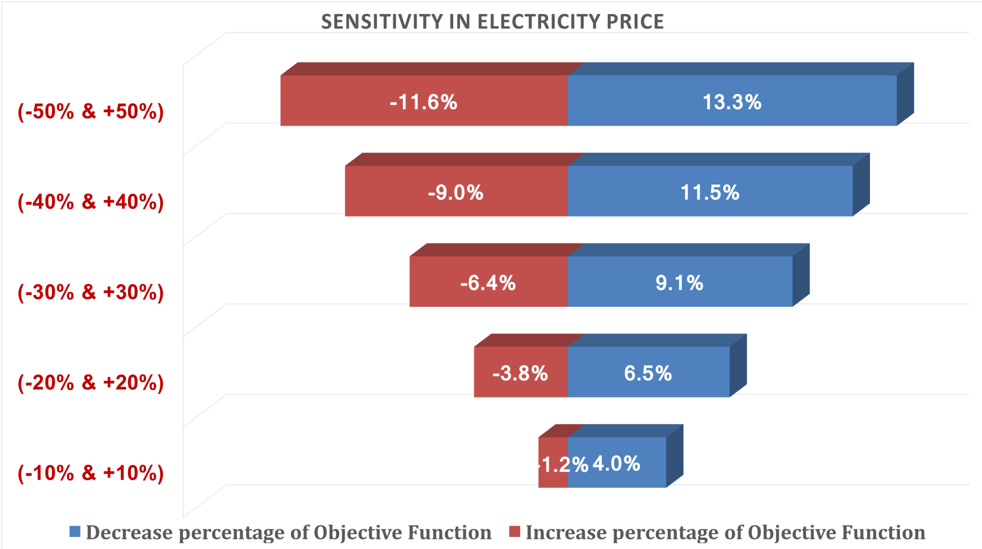


Figure 9: sensitivity in variable electricity price

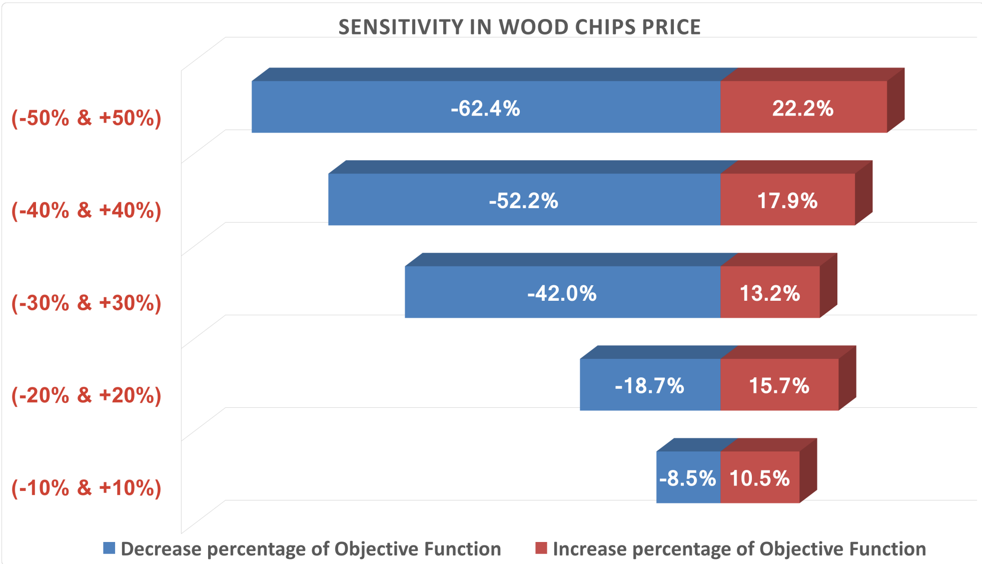


Figure 10: sensitivity in variable wood chips

It is easy to understand that the increase of the electricity price and the decrease of the cost of wood chips will optimize objective function. The former can be explained as profit rising by selling electricity, and the latter can be understood as it lower the producing cost directly.

First of all, the increase of electricity price, as well as the decrease of wood chips, which are both beneficial, shows a huge difference in the influence to the objective function. It is obvious that with the same level of change(for example electricity price increases 10%

and wood chips price decreases 10%), both of the factors have a great cost reduction. Especially when electricity price increases by 50%, the value of the total objective function in $scenario_2$ decreased by 11.6%. However, when the wood chips price decreases by 50%, the value of the total objective function in $scenario_2$ decreases by 62.4%. Though the result of wood chips declined dramatically, the reason can be understood as follows: With the price going down of wood chips, the CHP unit can be utilized more and at the same time more electricity will be produced that would make a greater profits as well. As a consequence of that, the objective function can be much lower than effectively price with the same variational range.

On the other hand, when the electricity price declines and the price of wood chips increases, the situation will be vice versa. The wood chips side still influences the objective function more than electricity price. At the bottom of electricity price(decreases by 50%), the value function will be 13.3% higher than the original value of $scenario_2$. However, the result contributed by this value here can only contend with the result from a medium enhanced wood chips price (increases by 30%). When the wood chips price increases 50%, the value function will be 22.2% higher than the original one in $scenario_2$, which is rational according to the data.

In summary, as the two factors given in this sensitivity analysis, the wood chips price factor should be considered as key factor compare to electricity price. This conclusion can help producer to be more aware of the portfolio, which leads to optimal profit.

5 Conclusion

The model has been developed step by step as it is stated before. Accordingly, the model was ameliorated by in-depth study. In short, results are stated below.

(1) Operation schedule analysis:

By employing the mathematical model in different scenarios, the result can be as follows. CHP unit is operated on high generating level as prominent resource of basic demand, NGB is to serve peak demand, HS plays an role of provisional supply to fulfill the demand temperately. (i.e. CHP production is insufficient)

(2) Stochasticity analysis:

a) Electricity prices: CHP heat production level has became more stable and higher while the natural gas heat boiler shows opposite tendency. In addition, the heat storage scarcely operates during the period. The stochasticity analysis makes the optimal result closer to the reality supplementing. b) Heat demand: Production level of CHP, NGB and HS shows unconspicuous change compare to the former one.

(3) Sensitivity analysis:

Wood chips price owns more dominance in comparison with electricity price. Thereout, manufacturers would be more sagacious hodling a perspective like that.

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A Abbreviation

Abbreviation	Explanation
t	Time periods /t1*t168/
i	Units /chp, gas, storage/
z	Total costs including the benefits from sale of electricity (euro)
d(t)	Heat demand
b	Benefits by selling electricity (euro)
elec(t)	Price of electricity in day ahead market
u(i,t)	Online status
u_init(i)	Initial online status
v(i,t)	Start-up status
p(i,t)	Heat production provided to customers (MWh)
su(i)	Start-up costs (euro per MW)
om(i)	O&M costs (euro per MWh input)
r(i)	Ramp rate
hmax(i)	Maximum heat generation level (MW)
hmin(i)	Minimum heat generation level (MW)
scen_d(s)	Probability of the scenario occurrence of heat demand
scen_p(s)	Probability of the scenario occurrence of electricity price
	CHP
chp_feed	CHP maximum feed level
chp_minld	CHP minimum load (fraction of full load)
chp_eheat	CHP heat efficiency
chp_eelec	CHP electricity efficiency
ratio	Heat to power ratio
wc	Price of wood chips (euro per MWh)
	Natural Gas Heat Boiler
ng_feed	Natural gas feed level
ng_eheat	Natural gas heat boiler heat efficiency
ng	Price of natural gas (eruo per MWh)

Abbreviation	Explanation
ng_minld	Natural gas heat boiler Minimum load (fraction of full load)
	Solar Heat Plant
sp(t)	Solar heat production per m^2
solar(t)	Solar heat production
	Heat Storage
y(i,t)	Open status for heat charge to heat storage unit
hs_cha(i,t)	Heat charge level (MWh)
hs_sto(i,t)	Heat storage balance level (MWh)
hs_e	Heat storage efficiency
hs_maxsto	Heat storage maximum storage level (MWh)
hs_minsto	Heat storage minimum storage level (MWh)
hs_maxcha	Heat storage maximum charge level (MWh)
hs_mincha	Heat storage minimum charge level (MWh)
hs_inisto	Heat storage initial storage level (MWh)

B GAMS code

```
option optcr = 0.0001

Sets

t time periods /t1*t168/

i units /chp, gas, storage/

*Assuming that we have perfect knowledge of solar, the heat production can be predicted.

sub1(i) /chp/

sub2(i) /gas/

sub3(i) /chp,gas/

subInit(t) /t1/

sub4(t)  /t2*t168/

sub5(i) /storage/


Parameters

hmax(i)  maximum heat generation level (MW) /storage 500/

hmin(i)  minimum generation level (MW) /storage 50/

su(i)     start-up costs (euro per MW)

 /chp 80

gas 0

  storage 0/

om(i)     O&M costs (euro per MWh input) /chp 1

gas 1.1

storage 0 /

r(i)     ramp rate                    /chp 0.85

                                      gas 0.9

                                    storage 1 /

u_init(i) initial online status        /chp 1

                                        gas 1

                                      storage 1/;

Scalar

*chp

chp_feed  CHP maximum feed level /500/

chp_minld CHP minimum load (fraction of full load) /0.15/

chp_eheat CHP heat efficiency /0.8458/

chp_eelec CHP electricity efficiency /0.2859/

ratio heat to power ratio /0.3415/

wc price of wood chips(euro per MWh) /34.35/

*natural gas

ng_feed  Natural gas feed level /350/

ng_minld Natural gas heat boiler Minimum load (fraction of full load) /0.15/

ng_eheat Natural gas heat boiler heat efficiency /1.05/

ng price of natural gas(euro per MWh) /37.00/

*heat storage (hot water tank)

hs_maxsto  Heat storage maximum storage level (MWh) /4500/

hs_minsto  Heat storage minimum storage level (MWh) /800/

hs_maxcha  Heat storage maximum charge level(MWh)   /400/

hs_mincha  Heat storage minimum charge level(MWh)   /10/
```

```
hs_inisto  Heat storage initial storage level (MWh) /800/

hs_e      Efficiency  /0.95/

;

*Scenario 1 data

$call =xls2gms r=M5:N172 i=Modeldata.xls o=demand.inc

Parameters

d(t)    demand

/

$include demand.inc

/;

$call =xls2gms r=A5:B172 i=Modeldata.xls o=power.inc

Parameters

elec(t)  price of electricity in day ahead market

/

$include power.inc

/;

$call =xls2gms r=Y5:Z172 i=Modeldata.xls o=solar.inc

Parameters

sp(t)  solar heat production per m^2

/

$include solar.inc

/;

Parameters

solar(t) solar heat production;

solar(t)=sp(t)*25000/1000 ;

hmax('chp')= chp_feed*chp_eheat;

hmin('chp')=
chp_feed*chp_minld*chp_eheat;

hmax('gas')= ng_feed* ng_eheat;

hmin('gas')= ng_feed*chp_minld*
ng_eheat;


Variables

b benifits by selling electricity(Euro)

z total costs including the benifits from sale of electricity (Euro)

u(i,t)   online status

v(i,t)   start-up status

y(i,t)   open status for heat charge

p(i,t)   heat production  (MWh)

hs_cha(i,t) heat charge (MWh)

hs_sto(i,t) heat storage(MWh)

;

free variable

z

b;

positive variable

p

hs_sto

hs_cha

v;

binary variables

u

y;
```

```
Equation

maxgene(i,t) maximum heat generation for all units (MWh)

mingene(i,t) minimum heat generation for all units (MWh)

maxcharge(i,t) minimum storage level (MWh)

mincharge(i,t) minimum charge level(MWh)

maxstorage(i,t) maximum storage level (MWh)

minstorage(i,t) minimum storage level (MWh)

storagebalance(i,t) heat storage balance(MWh)

ramp(i,t) ramp rate constraints

benifits benifits of selling electricity

costs total costs

startup(i,t) startup constraint for chp&ng in all periods

demand(t) heat demand (MWh);

maxgene(i,t).. p(i,t) =l= hmax(i)*u(i,t);

mingene(i,t).. p(i,t) =g= hmin(i)*u(i,t);

maxcharge(i,t)$sub5(i).. hs_cha(i,t) =l= hs_maxcha*y(i,t);

mincharge(i,t)$sub5(i).. hs_cha(i,t) =g= hs_mincha*y(i,t);

maxstorage(i,t)$sub5(i)..hs_sto(i,t) =l= hs_maxsto;

minstorage(i,t)$sub5(i)..hs_sto(i,t) =g= hs_minsto;

storagebalance(i,t)$sub5(i).. hs_sto(i,t) =e=

        (hs_sto(i,t-1)+hs_cha(i,t)*hs_e-p(i,t)/hs_e)$sub4(t)

        +(hs_inisto+hs_cha(i,t)*hs_e-p(i,t)/hs_e)$subInit(t);

ramp(i,t).. p(i,t)-p(i,t-1) =l= r(i)*hmax(i);

benifits.. b =e= sum((i,t)$sub1(i), p(i,t)*ratio*elec(t)) ;

costs..  z =e= sum(t,sum(i$sub1(i), p(i,t)*om(i)/chp_eheat + wc*p(i,t)/chp_eheat+ v(i,t)*su(i)*chp_feed - p(i,t)*ratio*elec(t))+  sum(i$sub2(i), p(i,t)*om(i)/ng_eheat + ng*p(i,t)/ng_eheat

+ v(i,t)*su(i)*ng_feed) );

startup(i,t)$sub3(i)..  (u(i,t)-u_init(i))$subInit(t) +(u(i,t)-u(i,t-1))$sub4(t) =l=v(i,t);

*electricity generation = heat generation(p(i,t))*ratio

demand(t).. d(t)=e= sum(i,p(i,t))-sum(i$sub5(i),hs_cha(i,t)) + solar(t);

Model EA /all/;

Solve EA using mip minimizing z;

Display  p.l, hs_sto.l, hs_cha.l, b.l, z.l;

*Export data to Excel

execute_unload "results.gdx" z.l p.l hs_sto.l hs_cha.l

execute 'gdxxrw.exe results.gdx var=z.l rng=Scenario1!A1:FX3'

execute 'gdxxrw.exe results.gdx var=p.l rng=Scenario1!A4:FX10'

execute 'gdxxrw.exe results.gdx var=hs_sto.l rng=Scenario1!A11:FX13'

execute 'gdxxrw.exe results.gdx var=hs_cha.l rng=Scenario1!A14:FX17'
```

C Results figures

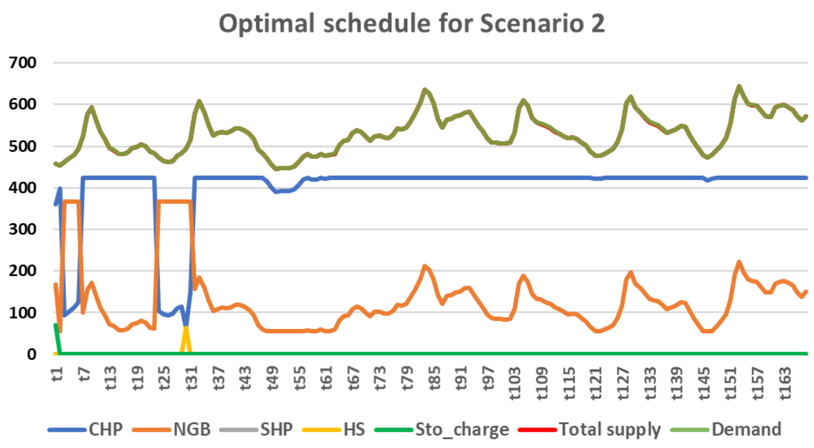

Figure 11: Optimal schedule for Scenario 2

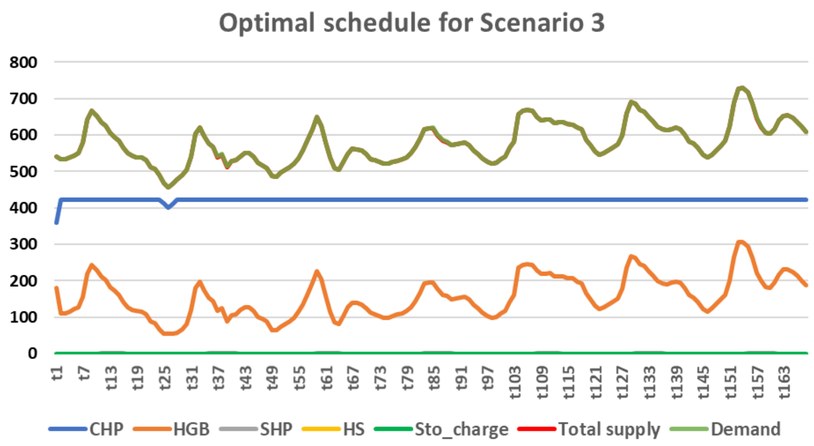

Figure 12: Optimal schedule for Scenario 3

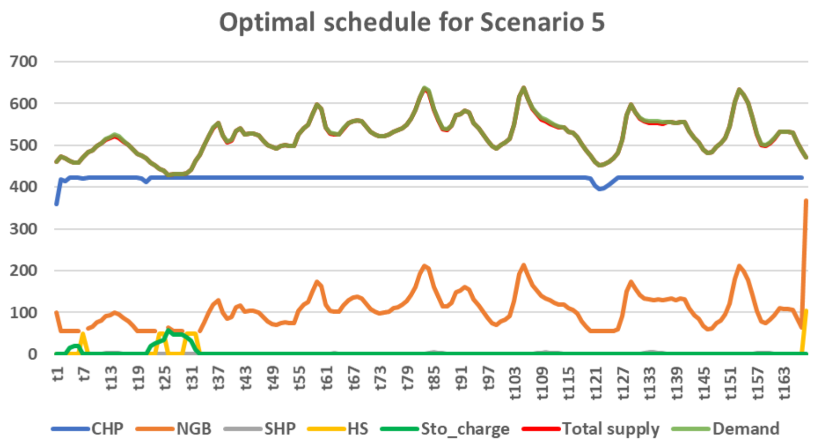

Figure 13: Optimal schedule for Scenario 5

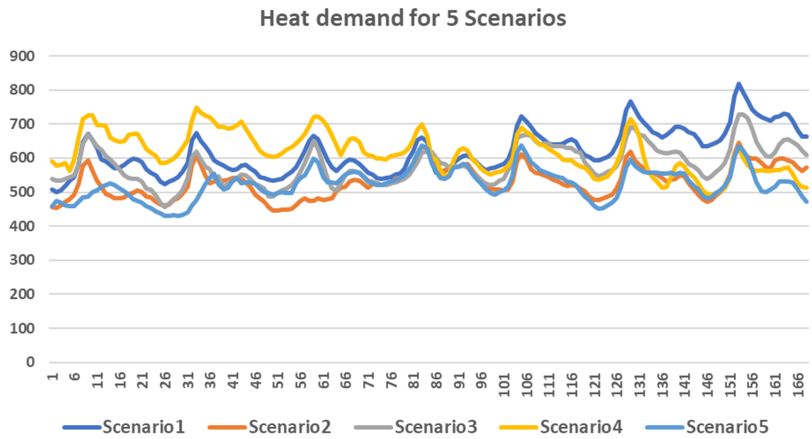

Figure 14: Heat demand for 5 Scenarios

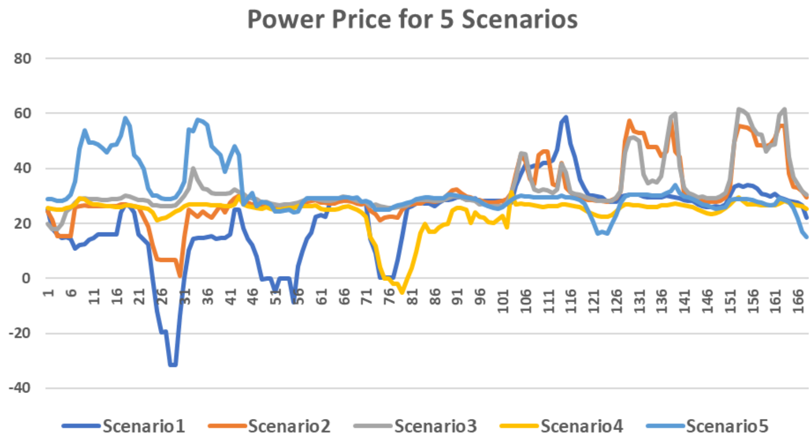

Figure 15: Power Price for 5 Scenarios

D Contribution sheet

X = Major				
x = Minor				
Model part	**Ziyi Liu**	**Chuyi Tong**	**Yihao Sun**	**Yingrui Li**
Mathematical Model	x	x	x	x
GAMS-Unit Commitment Model for 4 Units and 5 Scenarios	X	x		
GAMS-Stochastic Analysis	x	X		x
GAMS-Sensitivity Anslysis			X	x
Report part				
Section	**Ziyi Liu**	**Chuyi Tong**	**Yihao Sun**	**YIngrui Li**
1 Introduction	x			X
2 Methodology				
2.1 Isolated model in different units	x	X	X	x
2.2 Model integration	X	x	x	
3 Results				
3.1 Operation Schedule Analysis	X			x
3.2 Shadow Value of the Constraints	X	X		
4 Interpretation				
4.1 Stochasticity Analysis		X	x	
4.2 Sensitivity Analysis			X	x
5. Conclusion	x			X

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