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Demand Variability and Mismatches in the Cogeneration of Power and Process Heat*

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Abstract

This paper proposes a screening method for evaluating the cost penalty of alternative cogeneration solutions intended to handle variable-and-mismatched demands of power and heat. The method uses a simplified model for off-design performance that is sufficiently reliable for screening purposes.

The method is explained. The example of a stand-alone gas-turbine-power cogeneration system supplying given variable demands of power, cooling and heating of mismatched profiles is considered. A suitable basic configuration is investigated. A solution for a case with time-independent power-tracking products is obtained. The solution is run through the variable demand cycle to reveal the resulting fuel penalty. Improved design points of the time-independent solution as well as structural modifications aiming at reducing the penalty are introduced and the investigation is reiterated. The results of the various solutions are compared for cost effectiveness.

The analysis shows complex interactions between the set design points of solutions and the profiles of the products' demands that can obscure insight. Screening methods become most helpful for good engineering judgment. Reliable screening methods may reshape the cogeneration design practice for variable demands particularly in the field of air conditioning.

Key words: cogeneration, cogeneration demand variability, cogeneration mismatches, design screening

1. Introduction

Designers of energy systems face two classes of design problems. Class 1 problems are base-load design problems. Most of the time fueling and production are time-independent. Class 2 problems are variable-load design problems. Fueling and/or production are always time-dependent.

Fossil fueled systems producing storable products and base-load power generation systems belong to class 1. Solar energy fueled systems and systems cogenerating variable demands of power and process heat belong to class 2.

For class 1 problems, the production rate is well-defined by a constant demand rate. Designing all system devices for minimum cost, given the demand rate, becomes an important and appropriate objective. A system of a given configuration will operate most of the time at the design demand rate. The loading and the efficiency of each device in the system are optimized such that the overall system cost

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incurred by fuel and devices, allowing for maintenance, is minimized.

For class 2 problems, a design satisfying minimum cost still needs to be sought but a constant load design cannot guarantee minimum cost. For example, for a power-and-heat cogenerating system, the system may operate for a duration as low as 1% of the time at maximum power demand and, for a large percentage of the time, at say 70% of the maximum power demand. Having the optimal design point meet the short maximum power duration is meaningless, while having it meet the 70% demand may be under-designing, and having it meeting the minimum is surely under-designing. Moreover, the produced heat rate associated with the power demand is often different from the heat demand resulting in a mismatch between the heat available and heat demand.

To evaluate the penalty of both the variable and the mismatched aspects of demands in a cogenerating system, a stand-alone (grid-independent) gas turbine-based system producing power as well as chilled and hot water for cooling and heating purposes is considered. Hypothetical power and thermal loads capturing typical variations and mismatches are assumed for a repeatable summer demand cycle. This paper introduces a methodology for screening variable-demands cogeneration solutions for minimum production cost. A follow-up paper will evaluate the quality of the simplified off-design performance model against a more sophisticated one.

2. Problem Complexity

In mathematical terms, the decision variables $\{Y\}$ of a system computational algorithm (given the dependent variables $\{x\}$ along with their constraining relations) are optimized for a given cost objective function J by the following two sets of equations:

Class 1 problems:

$$\partial J(\{Y\})/\partial Y_i = 0,\ i = 1,2\ldots n \text{ decisions} \qquad (1)$$

Class 2 problems

$$\partial \left[{}_0\!\int^{\tau} J(\{Y\},t)dt \right] / \partial Y_i = 0,\ i = 1,2\ldots n \text{ decisions} \qquad (2)$$

In both equations the constraining relations are satisfied. In equation (2) τ is the time span of repeatable demand cycle. Obviously, handling the differentials of the time integral of equation (2) is much more difficult than handling those of the time-independent equation (1) which is already complicated by the large number of decision variables. However few methodologies are now available to handle equation (1). References (Gaggioli, 1983; Torres et al., 1996) provide examples of these methodologies.

One way of dealing with equation (2) is to optimize the configuration and the devices for time-independent situation, then run the obtained solution in an operation mode with a chosen control strategy through the load profiles to compute the additional fuel penalizing the objective J. The operation mode requires the burden of computing the off-design performance of each device in the system followed by the derivation of the off-design performance of the system itself for that control strategy. Convergence to a system performance point in this derivation is not always guaranteed. The computational cycle is then repeated with modified decisions in the direction of minimizing J. This is all right if we have one configuration to investigate. Unfortunately, a larger number of configurations emerge for class 2 problems compared to class 1 problems. This is caused by the large variability in demand profiles and the large number of design decision variables.

3. A Simplified Operation Model

Figure 1 shows the optimal design procedure for both class 1 and 2 problems. Class 1 problems go through 4 basic procedures (describe, compute, optimize and reconfigure). Class 2 problems go through two further procedures (obtain off-design performance, operate).

As mentioned earlier, the off-design procedure is lengthy and not free from convergence problems while the number of configurations to be examined is large. The procedure is greatly enhanced if the problem can be transformed somehow to a class 1 problem. This may be achievable by a simplified operation model. The following establishes the one used in this paper.

Let the model assume that the only thing known about the off-design performance of a system is an overall system efficiency as a function of the variation of one of its products, say power. Let the model establish actual operation by a deviation from ideal operation. The ideal operation assumes constant efficiencies where all off-design efficiencies of system components, as well as that of the system, remain constant at their design values. The deviation from this ideal off-design performance is derived from the assumed overall system performance equation.

An overall system power-to-fuel efficiency may be adequately presented by a quadratic equation in load fraction X, as

$$\eta_s = P/F = a + b * X + c * X^2 \qquad (3)$$

where η_s is the overall system power efficiency, P is the power produced, F is the fuel used at P, X is the power load fraction P/P_{adp}. P_{adp} is the average daily peak loading. P^o is design power at $X=X^o$ where X^o has a value around 1 depending on the duration of peak loads of the demand profiles. In this study $X^o = 0.9$ is considered appropriate for the given power profile. The constant a is an extrapolated efficiency at X=0. The ratio of efficiency at X=0 to that at X^o defines a unique set of off-design performance efficiencies as illustrated in *Figure 2*. The selected ratio should be quoted from operating plants of similar application.

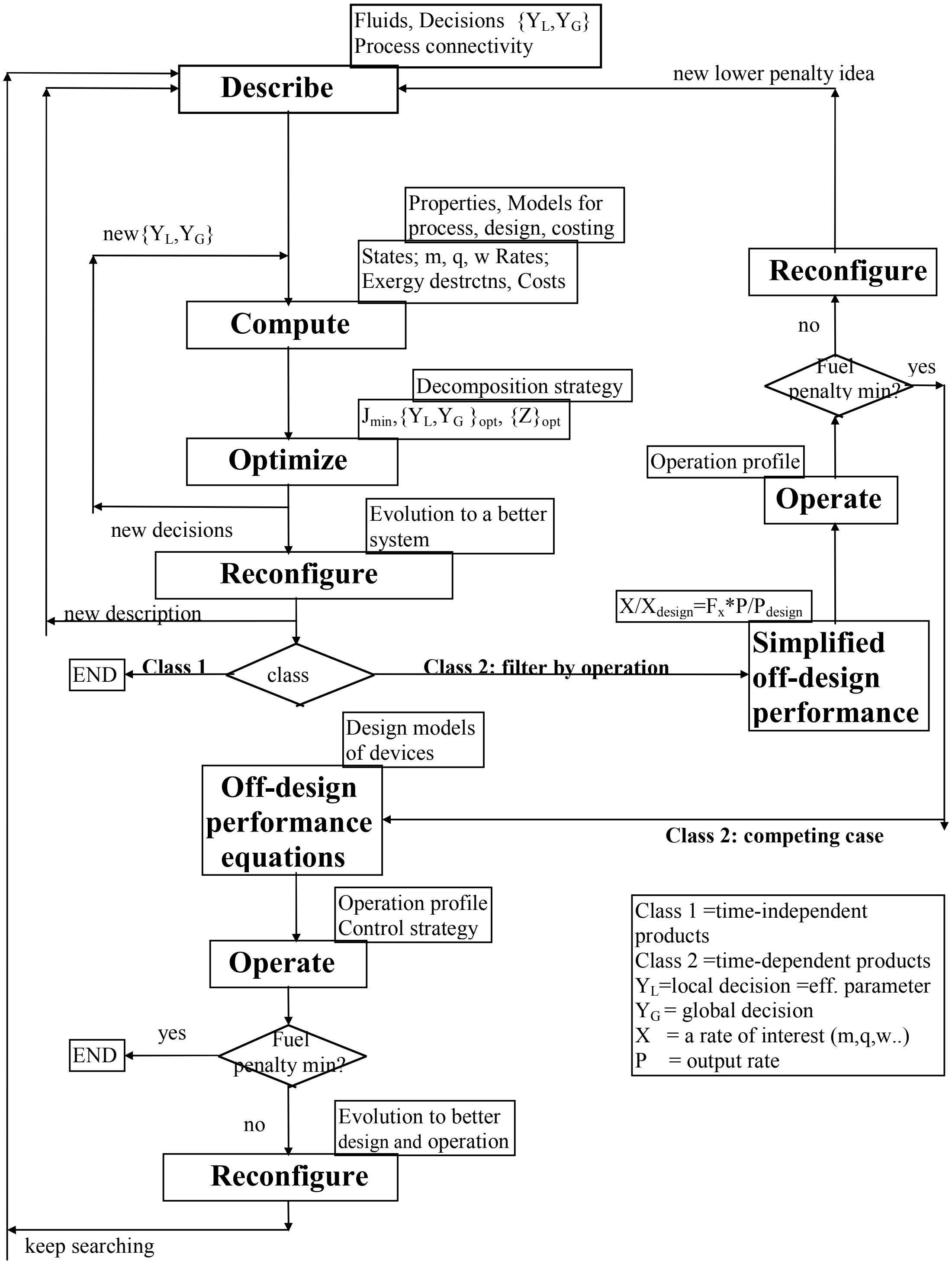


Figure 1. Optimal system design of time-independent and time-dependent products

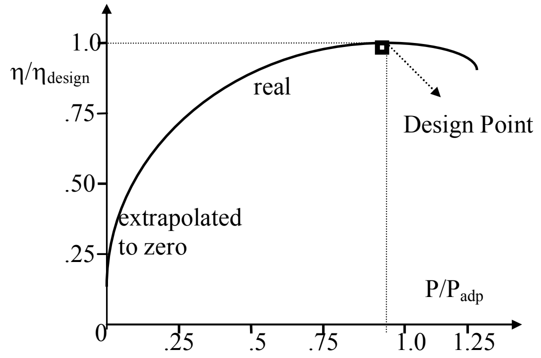


Figure 2. Overall system efficiency ratio vs. load fraction.

At $X= X^o$, the fuel at design point is F^o, and the design efficiency is η_s^o.

A heat exchange and an exergy destruction at $X=X^o$ are Q_i^o and D_i^o

Fuel at any power demand

$$F = P/\eta_s \tag{4}$$

Fuel assuming design efficiency η_s^o

$$F_{\eta so} = P/ \eta_s^o \ . \tag{5}$$

Fuel penalty at any power demand

$$\delta F= F- F_{\eta so} = (1/\eta_s - 1/\eta_s^o)*P. \tag{6}$$

Exergy of fuel penalty

$$\delta E_F = \delta F*E_F/H_h \tag{7}$$

Heat deliverable at any power demand

$$Q=F- P = (1/\eta_s -1)*P \tag{8}$$

$$F_{\eta so} / F^o = P/P^o. \tag{9}$$

where E_F is the fuel exergy per unit mass and H_h is its higher heating value.

Let all heat exchanged be augmented by a factor F_Q and all exergy destructions be augmented by a factor F_D, each factor being >1. Then

$$F_Q = [{}_0\int^{\tau} (P*(1/\eta_s-1)/(1/\eta_s^o-1)* dt] / \tau \tag{10}$$

$$F_D = [{}_0\int^{\tau} (1+ \delta E_F / \Sigma D_i^o)* dt] / \tau \tag{11}$$

where D_i^o is an exergy destruction of a device at the system design point. For ideal operation $F_Q = F_D = 1$

In the model above, the change in off-design performance is only in the stream rates through the devices and not the states between the devices. The fuel penalty δE_F raises both the levels of heat exchanges and exergy destructions.

The model above is guided by a study made to predict the off-design performance of a simple combined cycle of a given control strategy from the design models of its devices (El-Sayed, 1999). The study showed the adequacy of a quadratic form of the overall system power/fuel efficiency. The study also showed uneven distribution of the fuel penalty as well as changes in system states in a way depending on the control strategy. For example at X = 0.8, the exergy destructions were 1.02 to 1.6 times their value at X^o-. The model above avoids the lengthy computations of the changes in the system states as a function of the power ratio X at the expense of assuming an even higher level of heat exchanges and exergy destructions and, in return, of examining a large number of configurations. However, when considering a most promising configuration, it is worthwhile to go through the lengthy computations as used in reference (El-Sayed, 1999).

4. The Investigated Problem

The basic system, *Figure 3*, consists of a simple gas turbine power unit burning natural gas, heat recovery steam generator, a single stage LiBr/H_2O absorption refrigeration subsystem for cooling, a steam heating coil for heating and a water heater for domestic use. Two recovery ideas are introduced: a gas turbine regenerator and a vapor-compression cooling unit. The numbers assigned to the devices and to the states for the purpose of computation are indicated. The problem has in total 33 devices, 60 states and 106 decision variables. The decision variables consist of 28 boundary pressures and temperatures, 53 efficiency parameters (local decisions), 5 global thermodynamic decisions, and 20 ground-rules decisions. Fuel and product prices and capital recovery rate are among the ground-rules decisions. The local and the global decisions can be handled by automated optimization. All the decisions can be changed manually. However, the boundary and ground rules decisions are kept constant most of the time.

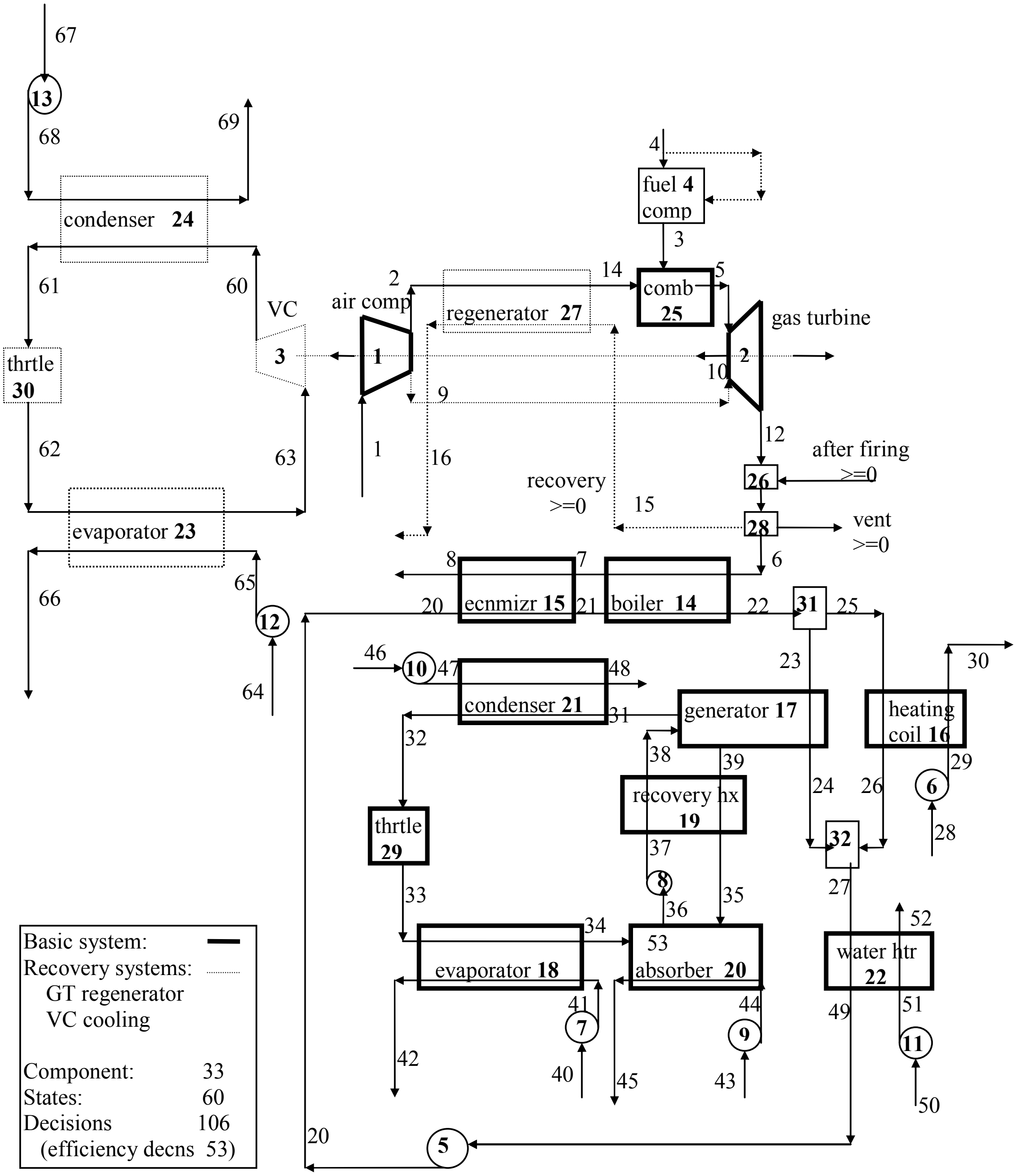
Figure 4 shows the demand profiles of power, cooling, heating and hot water assumed as given and the values that characterize their variability. The figure also shows the available power-matching cooling, heating and hot water profiles for the reference case design. For the convenience of establishing the method, the period τ of repeatable pattern is taken as 24 hrs. The minimum duration of a load is taken as one hour. Neither the period nor the duration put any limitations onto the method. In evaluating off design operation, it is helpful to think of the load factors of the demand profiles as time duration ratios of on-off operation at design conditions. However in this study the efficiency obeys a relation described by Eq. (2).

The basic system is first treated as time-independent (class 1) problem. A solution defined by constant and power-matching demands and a set of feasible decision variables {Y} is computed and then run through an automated and/or manual optimization process to minimize production cost by changing the decision variables. The treatment of class 1 problems is explained in detail elsewhere (El-Sayed, 1996; El-Sayed et al., 1999). The costing of devices is based on design models for the devices to respond to efficiency changes. They are, however, compared to available market-place prices, such as reference (RSMeans, 2000).

In this study the computations are augmented by an operation subroutine based on the simplified operation model described above. Any obtained solution, whether optimum or not, can be run through the operation repeatable times to compute the fuel penalty of variable demands. The objective function J is the production cost and is computed on two steps according to the equation:

$$J= (\text{cost of fuel+capital})_{\text{constant power matched demands}} + (\text{penalty cost of fuel+capital})_{\text{variable power mismatched demands}} \qquad (12)$$

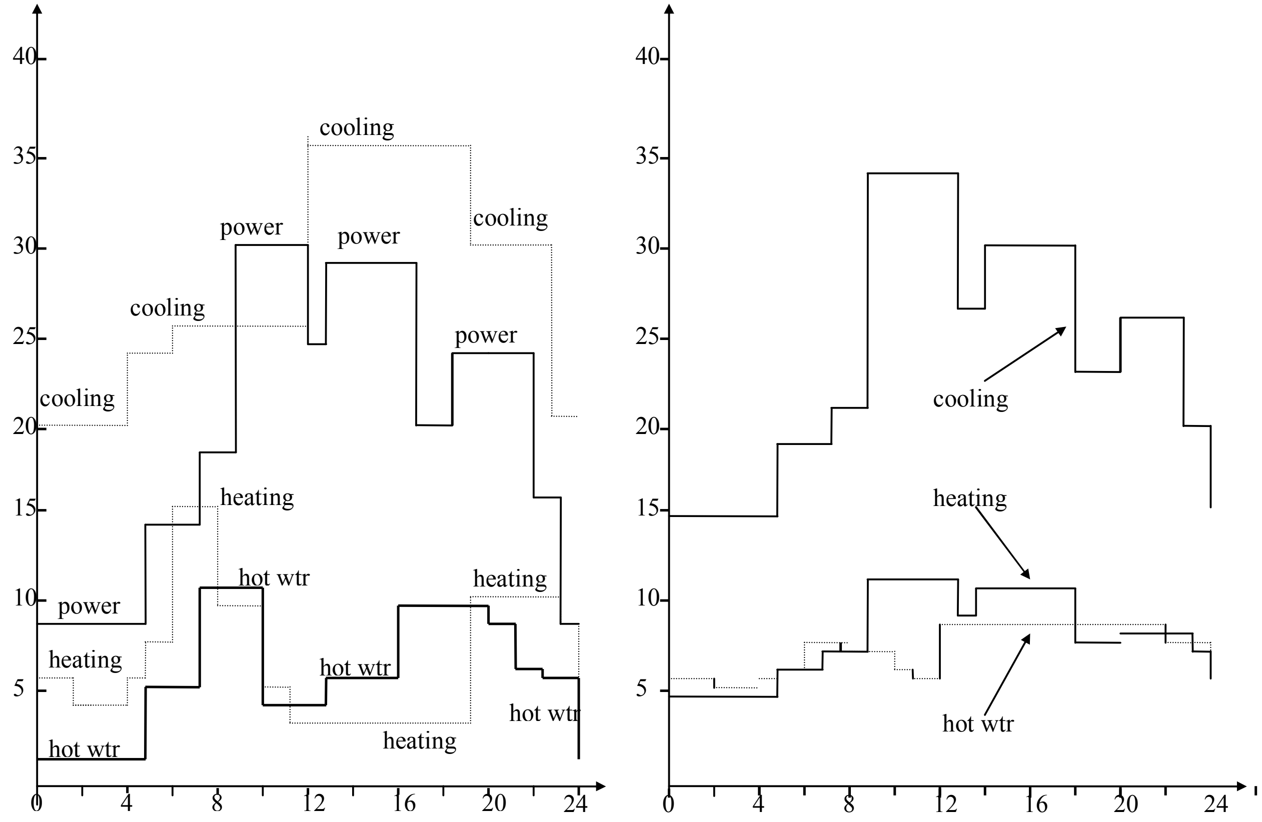
Other operation and maintenance costs are assumed constant ratios of fuel and capital.



Basic system:	▬
Recovery systems:	┈
GT regenerator	
VC cooling	
Component:	33
States:	60
Decisions	106
(efficiency decns	53)

33 represents a dump for streams 8,16,45,48,69 and the vent.

Figure 3. Flowsheet



DEMAND PROFILES

AVAILABLE PROFILES OF THE REFERENCE

MAIN FEATURS OF DEMAND PROFILES

Max and Min Power MW 30 & 8
Load Factor 0.6778

Max and Min Cooling MW 36 & 20
Load Factor 0.7940

Max and Min Heating MW 15 & 3
Load Factor 0.4389

Max and Min Hot Wtr MW 10 & 2
Load Factor 0.6000

Average Delivery MW 61.49
of MW Exergy 22.96

Figure 4. Demand and available profiles

The considered system handles mismatches simply by dumping and refiring. Hot gases are vented at the exit of the gas turbine when available heat is more than demanded and re-firing more fuel at the exit of the gas turbine when available heat is less than demanded. When heating and cooling demands are satisfied and excess heat goes to the domestic hot water, hot water is dumped.

A regenerator is proposed to recover heat from the vented gas by heating the air before entering the gas turbine combustion chamber.

A vapor-compression (R12 for the time being) refrigeration cycle for cooling is proposed to reduce re-firing when the absorption refrigeration cooling is less than demanded.
No measures are taken to recover heat from the dumped domestic hot water.

5. The Investigation Made

Several runs were made to investigate the influence of the basic system design points, the design points of recovery devices, and the degree of departure from ideal performance. *Figure 5* is a cost-efficiency diagram that shows the effect of the design efficiency of the system on its efficiency under time-dependent operation. Variable operation reduces efficiency and increases cost. However, higher design efficiency allows higher operating efficiency.

Table 1A of the appendix is a computer output presenting an investigation of eight runs. Run 1 has the reference design case of the basic system. Neither the regenerator nor the vapor-compression unit is cost-effective.

Run 2 has a time-independent design point of minimized production cost that happened to be a high-level efficiency run. The regenerator is not needed because of the absence of hot gas venting. The VC unit is needed and weakly cost-effective. Run 3 has the same design point as run 2 but the VC unit is sized on mean load rather than the maximum load of the reference run. The cost effectiveness was improved and provided room for an ice-making storage unit. Note that time-independent minimum cost does not necessarily mean time-independent maximum profitability. The latter depends on the market values of the four products.

Run 4 has a time-independent design point of low level efficiency of most of the devices of the basic system. The VC unit is not needed because of the lack of re-firing. The regenerator is strongly cost-effective having already room for storage medium for the energy of the vented hot gas. Run 5 uses a larger temperature terminal difference for regenerator and the cost-effectiveness improves further. Run 6 sizes the regenerator on mean load with a large cost-effective improvement.

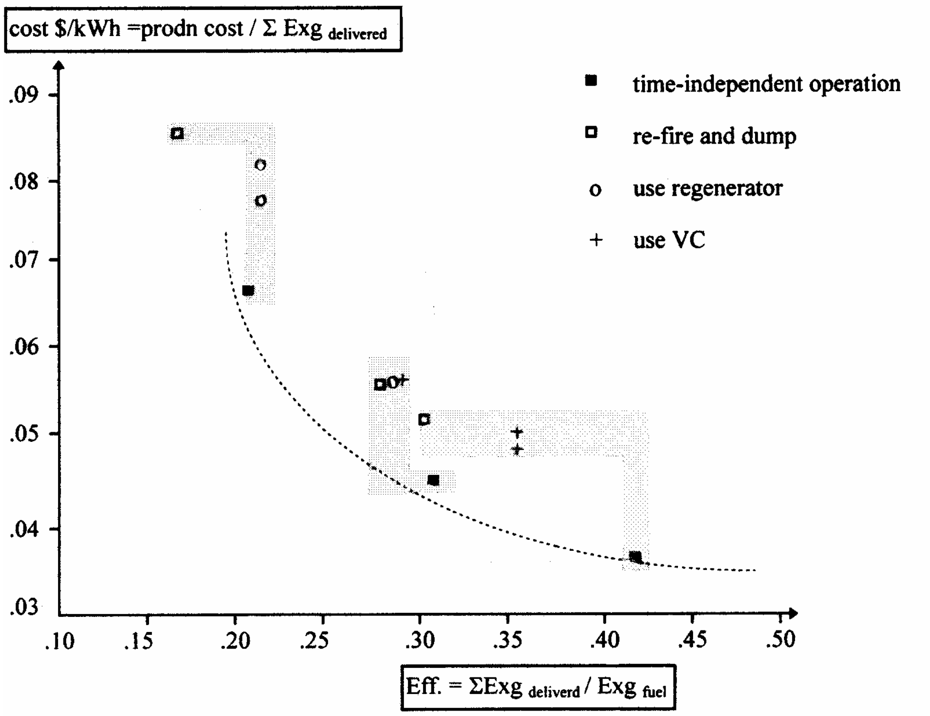


Figure 5. The cost-Efficiency Plane.

Run 7 and 8 reveal the sensitivity of run 1 to changes in the assumed overall system efficiency of the screening method. Run 7 assumes ideal operation of efficiency ratio of 1 at all off design loads. Run 8 assumes a variable ratio from 1 at design load to (-0.2) at zero extrapolated load (run 1 assumes an efficiency ratio of 0.2). For run 8, the deviation factors from ideal performance reached 1.5 but the cost increased by 6 % only from the ideal case of run 7.

The computer program of this paper and the detailed information on which *Figure 5* is based are available upon request free of charge. The following are some interesting features:

- Complex interactions exist between the design point of a cogenerating system and the demand profiles of the products. The complexity can obscure insight to improvement without running a sought design through the load profiles.

- Neither the regenerator nor the vapor compression unit was cost effective for the reference design case. Raising the design efficiency, the vapor compression unit became cost effective and the regenerator solution was not needed since no dumping was necessary. Lowering it, the regenerator became cost effective and the vapor compression solution was not needed because there was no re-firing. Assuming storage and sizing on mean load improved the cost effectiveness in both cases.
- The assumption of an overall system performance equation guided by experience from similar existing plants does not seem to affect the reliability of a screening method.

Runs assuming constant power production by allowing buying and selling transactions with the grid at the market-place power price have higher operation efficiency and lower unit production costs than those of the stand-alone case as shown by Table 3A of the Appendix. The value of the produced power influences both efficiency and cost.

6. Conclusions

The following observations are of general interest for load profiles, boundary conditions and ground rules similar to those of this investigation:

- Time-independent operation has the lowest unit production cost and the highest operation efficiency. Constant power production by fair buying and selling transactions with the grid are second-best choice. Wild load profiles should be avoided.
- For a given set of load profiles, the design point of a system influences the inefficiency of operation and the recovery strategy of the simple dumping/re-firing solution.
- The large number of variables involved in load profiles and system design efficiency raises the importance of a screening method.
- A screening method assuming an overall system operation efficiency quoted from similar existing plants will have little effect on the reliability of the method.

APPENDIX

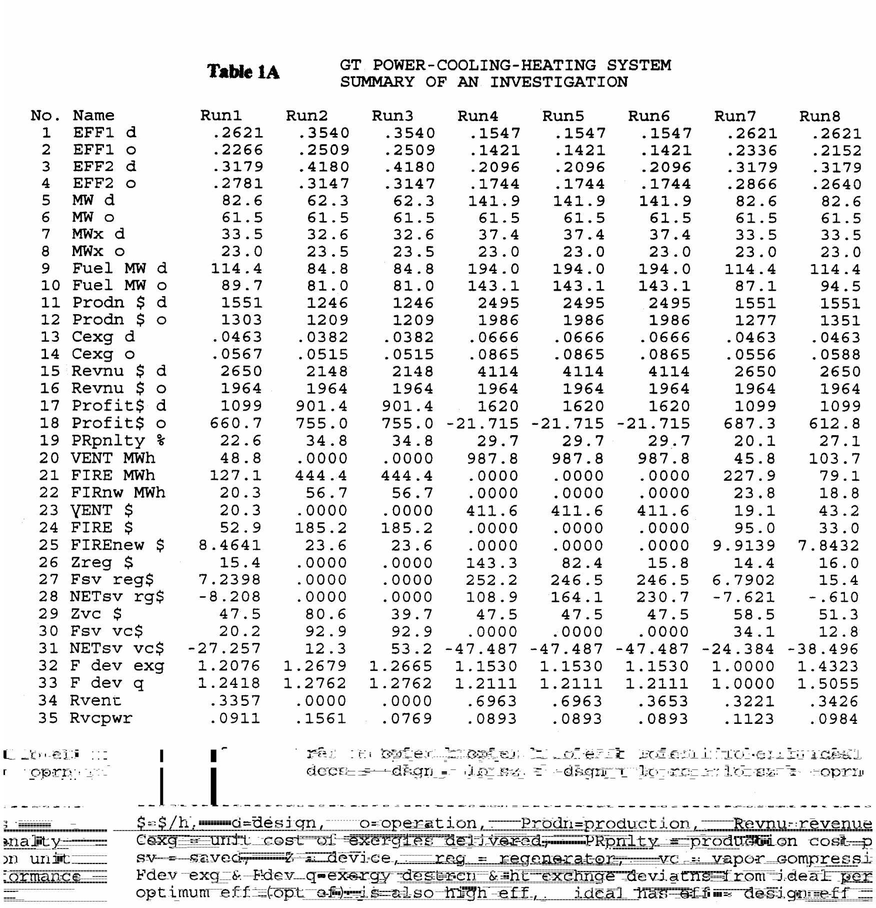


Table 1A GT POWER-COOLING-HEATING SYSTEM
SUMMARY OF AN INVESTIGATION

No.	Name	Run1	Run2	Run3	Run4	Run5	Run6	Run7	Run8
1	EFF1 d	.2621	.3540	.3540	.1547	.1547	.1547	.2621	.2621
2	EFF1 o	.2266	.2509	.2509	.1421	.1421	.1421	.2336	.2152
3	EFF2 d	.3179	.4180	.4180	.2096	.2096	.2096	.3179	.3179
4	EFF2 o	.2781	.3147	.3147	.1744	.1744	.1744	.2866	.2640
5	MW d	82.6	62.3	62.3	141.9	141.9	141.9	82.6	82.6
6	MW o	61.5	61.5	61.5	61.5	61.5	61.5	61.5	61.5
7	MWx d	33.5	32.6	32.6	37.4	37.4	37.4	33.5	33.5
8	MWx o	23.0	23.5	23.5	23.0	23.0	23.0	23.0	23.0
9	Fuel MW d	114.4	84.8	84.8	194.0	194.0	194.0	114.4	114.4
10	Fuel MW o	89.7	81.0	81.0	143.1	143.1	143.1	87.1	94.5
11	Prodn $ d	1551	1246	1246	2495	2495	2495	1551	1551
12	Prodn $ o	1303	1209	1209	1986	1986	1986	1277	1351
13	Cexg d	.0463	.0382	.0382	.0666	.0666	.0666	.0463	.0463
14	Cexg o	.0567	.0515	.0515	.0865	.0865	.0865	.0556	.0588
15	Revnu $ d	2650	2148	2148	4114	4114	4114	2650	2650
16	Revnu $ o	1964	1964	1964	1964	1964	1964	1964	1964
17	Profit$ d	1099	901.4	901.4	1620	1620	1620	1099	1099
18	Profit$ o	660.7	755.0	755.0	-21.715	-21.715	-21.715	687.3	612.8
19	PRpnlty %	22.6	34.8	34.8	29.7	29.7	29.7	20.1	27.1
20	VENT MWh	48.8	.0000	.0000	987.8	987.8	987.8	45.8	103.7
21	FIRE MWh	127.1	444.4	444.4	.0000	.0000	.0000	227.9	79.1
22	FIRnw MWh	20.3	56.7	56.7	.0000	.0000	.0000	23.8	18.8
23	VENT $	20.3	.0000	.0000	411.6	411.6	411.6	19.1	43.2
24	FIRE $	52.9	185.2	185.2	.0000	.0000	.0000	95.0	33.0
25	FIREnew $	8.4641	23.6	23.6	.0000	.0000	.0000	9.9139	7.8432
26	Zreg $	15.4	.0000	.0000	143.3	82.4	15.8	14.4	16.0
27	Fsv reg$	7.2398	.0000	.0000	252.2	246.5	246.5	6.7902	15.4
28	NETsv rg$	-8.208	.0000	.0000	108.9	164.1	230.7	-7.621	-.610
29	Zvc $	47.5	80.6	39.7	47.5	47.5	47.5	58.5	51.3
30	Fsv vc$	20.2	92.9	92.9	.0000	.0000	.0000	34.1	12.8
31	NETsv vc$	-27.257	12.3	53.2	-47.487	-47.487	-47.487	-24.384	-38.496
32	F dev exg	1.2076	1.2679	1.2665	1.1530	1.1530	1.1530	1.0000	1.4323
33	F dev q	1.2418	1.2762	1.2762	1.2111	1.2111	1.2111	1.0000	1.5055
34	Rvent	.3357	.0000	.0000	.6963	.6963	.3653	.3221	.3426
35	Rvcpwr	.0911	.1561	.0769	.0893	.0893	.0893	.1123	.0984

$=$/h, d=design, o=operation, Prodn=production, Revnu=revenue
Cexg = unit cost of exergies delivered, PRpnlty = production cost p
sv = saved, Z = device, reg = regenerator, vc = vapor compressi
Fdev exg & Fdev q=exergy destrcn & ht exchnge deviatns from ideal per
optimum eff (opt ef) is also high eff, ideal has eff = design eff

Table 2A

```
GT POWER-COOLING-HEATING SYSTEM
STAND-ALONE COGENERATION PLANT
OPERATION ALLOWS FOR OFF-DESIGN INEFFICIENCY

Sys  Q in Q out   NetQin  NetWout Exin    Exout   Disspn Eff2  Eff1  Ef2  efwl
                  Btu/lb reference mass             in-out
 1   309.5  229.4   80.1   81.1  286.0   15.6  270.3 .3179 .3001 .7197 .2621

             Design for a Net Power   Operate for Given Load Profiles

Efficiency P/F     =  .2621                 .2266
Efficiency 2nd Law =  .3178                 .278

Ineffcncy Dsspn fctor  = 1                  1.2
Ineffcncy heat factor  = 1                  1.24

Overall Extensive Parameters
Nominal power       kW   =  31013
net power           kW   =  30000           20333
cooling             kWt  =  33356           28583
heating             kWt  =  10661           6583
hot water           kWt  =  8577            6000
prodcts'exergy      kW   =  33495           22969
prodcts'energy      kWt  =  82594           61499
pmps+fuelcomp       kW   =  1013
Fuel input          kWt  =  114442          89715
Ref fuel            kWt  =  114442

Overall Costs
Fuel            $/h     =  1144.42          897.15
Equipment       $/h     =  406.28           406.28
power           $/h     =  1350
cooling         $/h     =  1000.7
heating         $/h     =  213.22
hot water       $/h     =  85.77
Revenues        $/h     =  2649.69          1964.16
Production cost $/h     =  1550.7           1303.44
Prd/unit exergy $/kWh   =  .046             .056
Profit          $/h     =  1098.99          660.72
Ref             $/h     =  1098.99

Penalties
Production penalty   $/Kwh= .01        % penalty=      22.5
Gas Venting penalty  $/h   = 20.3      MWh fuel =      48  included in fuel
Hot wtr dump penalty $/h   = 15.7      MWh fuel =      37  included in fuel
After Firing penalty $/h   = 52.9      MWh fuel =      127
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Table 3A

```
GT POWER-COOLING-HEATING SYSTEM
BUY-AND-SELL GRID-POWER COGENERATION PLANT
SUMMARY OF AN INVESTIGATION

No. Name          Run1     Run2     Run3     Run4     Run5     Run6     Run7     Run8
 1  EFF1 d       .2621    .3539    .1547    .2621    .2621    .2621    .2621    .2621
 2  EFF1 o       .2345    .2550    .1547    .2345    .2345    .1560    .2621    .1560
 3  EFF2 d       .3179    .4179    .2096    .3179    .3179    .3179    .3179    .3179
 4  EFF2 o       .2925    .3252    .1929    .2925    .2925    .3892    .2180    .3892
 5  MW d          55.1     41.5     94.6     55.1     55.1     27.5     82.6     27.5
 6  MW o          61.5     61.5     61.5     61.5     61.5     61.5     61.5     61.5
 7  MWx d         22.3     21.7     25.0     22.3     22.3     11.2     33.5     11.2
 8  MWx o         23.0     23.5     23.0     23.0     23.0     23.0     23.0     23.0
 9  Fuel MW d     76.3     56.5    129.3     76.3     76.3     38.1    114.4     38.1
10  Fuel MW o     85.3     78.4    129.3     85.3     85.3     64.1    114.4     64.1
11  Prodn $ d     1034    831.2     1663     1034     1034    517.0     1551    517.0
12  Prodn $ o     1289     1215     1828     1307     1234     1260     1551     1260
13  Cexg d       .0463    .0382    .0666    .0463    .0463    .0463    .0463    .0463
14  Cexg o       .0561    .0518    .0796    .0569    .0537    .0549    .0675    .0549
15  Revnu $ d     1766     1432     2743     1866     1466    883.2     2650    883.2
16  Revnu $ o     1964     1964     1964     2066     1659     1964     1964     1964
17  Profit$ d    732.6    600.8     1080    832.6    432.6    366.3     1099    366.3
18  Profit$ o    775.2    848.8    236.0    791.9    575.2    716.5    703.5    716.5
19  PRpnlty %     21.2     35.4     19.4     22.9     16.0     18.5     45.8     18.5
20  VENT MWh      19.9    .0000    764.8     19.9     19.9    .0000    230.1    .0000
21  FIRE MWh     216.2    525.8    .0000    216.2    216.2    622.8    .0000    622.8
22  FIRnw MWh     38.1     80.4    .0000     38.1     38.1     95.7    .0000     95.7
23  VENT $      8.2805    .0000    318.7   8.2805   8.2805    .0000     95.9    .0000
24  FIRE $        90.1    219.1    .0000     90.1     90.1    259.5    .0000    259.5
25  FIREnew $     15.9     33.5    .0000     15.9     15.9     39.9    .0000     39.9
26  Zreg $      3.7878    .0000     58.1   3.7878   3.7878    .0000     26.6    .0000
27  Fsv reg$    2.9479    .0000    195.2   2.9479   2.9479    .0000     34.1    .0000
28  NETsv rg$    -.840    .0000    137.1    -.840    -.840    .0000   7.5678    .0000
29  Zvc $         46.3     83.9     46.3     46.3     46.3     94.9     94.9     94.9
30  Fsv vc$       74.2    185.6    .0000     74.2     74.2    219.6    .0000    219.6
31  NETsv vc$     27.9    101.7  -46.252     27.9     27.9    124.7  -94.943    124.7
32  F dev exg   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
33  F dev q     1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
34  Rvent        .1690    .0000    .6125    .1690    .1690    .0000    .4480    .0000
35  Rvcpwr       .1330    .2438    .1305    .1330    .1330    .5462    .1821    .5462

                   ref     optef    lo ef    hi by    lo by    lo pr    hi pr    lo pr
                 by sl    by sl    by sl    lo sl    hi sl    by sl    by sl    by sl

--------------------------------------------------------------------------------------
$=$/h,   d=design,   o=operation,   Prodn=production,   Revnu=revenues
Cexg = unit cost of exergies delivered,   PRpnlty = production cost penalty
sv = saved,   Z = device,   reg = regenerator,   vc = vapor compression unit
Fdev exg & Fdev q=exergy destrcn & ht exchnge deviatns from ideal performance
optimum eff (opt ef) is also high eff,   ideal has eff = design eff
```

Nomenclature

a	Constant
A	Surface area
b	Constant
c	Constant, a unit cost ($/kWh)
D	Exergy destruction rate (kW)
E	Flow exergy (kW)
F	Fuel rate (kW), deviation factor from ideally controlled operation
H	Heating value
J	Production cost objective function ($/h)
P	Power
x	Dependent variable
X	Load ratio demand/design
Y	Decision variable
Z	Cost of an energy conversion device

Subscripts

c	cooling
D, d	exergy destruction
f	fuel
G	global
h	heating, higher heating value
L	local
p	power
Q	heat exchange
s	First law efficiency
w	hot water
z	capital recovery rate

Superscripts

^{o}	design value

Greek Symbols

η	Efficiency
τ	Time period of a repeatable load profile

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