Integrated Thermal Power and Desalination Plant Optimization

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Introduction

In recent years, the preferred scheme for drinking water production facilities has been a thermal power plant integrated with a thermal desalination plant. The combined production of power and water is the most economical way to simultaneously satisfy the demands for electricity and water. Among the potential thermal power plant schemes, a gas-turbine-based combined-cycle power plant will cogenerate the steam needed for a desalination plant in the most economical manner.

In the Gulf countries, the demand for power and water varies significantly throughout the year. During winter months, when the load requirements for air conditioning are low, the demand for power is greatly reduced, while the demand for water remains fairly constant throughout the year. This leads to an under-utilization of 50-70% of the power generation capacity, effectively increasing the cost of the desalinated water. As pointed out by a MEDRC report, the water-to-power ratio may vary from 700 to 1600 m^3/day/MW. The variation in the electricity demand, expressed in terms of the ratio of the peak to the minimum demand, varies in the range of 4:1 to 5:1, while the peak-to-minimum water demand varies only from 1.3:1 to 1.4:1. Electricity demand varies seasonally and even hourly, while the water demand remains essentially constant.

This requires that the power plant be operated so as to maintain full output of steam under all load conditions. The demands on the flexibility of operation of such combined facilities are therefore quite severe since the power generation equipment must operate stably over a wide range. Such operation is not simple.

A system to optimize the power production under such conditions would provide sizable benefits to the operating companies if information is provided real-time to the operators. Due to the size of such facilities, which range from 700 to 1500 MW net power production and up to 100 Million Imperial Gallons per Day (MIGD) of fresh water, fuel reductions of even a small percentage can

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represent significant cost savings. To realize these savings, the optimization needs to be as accurate as possible and needs to provide advice for optimized operation in real-time.

This paper describes a technique for computer-simulation-based optimization of gas-turbine combined-cycle power plants integrated with Multi-Stage Flash (MSF) desalination units, as shown in Figure 1. The optimization technique can be applied to new and existing plants.

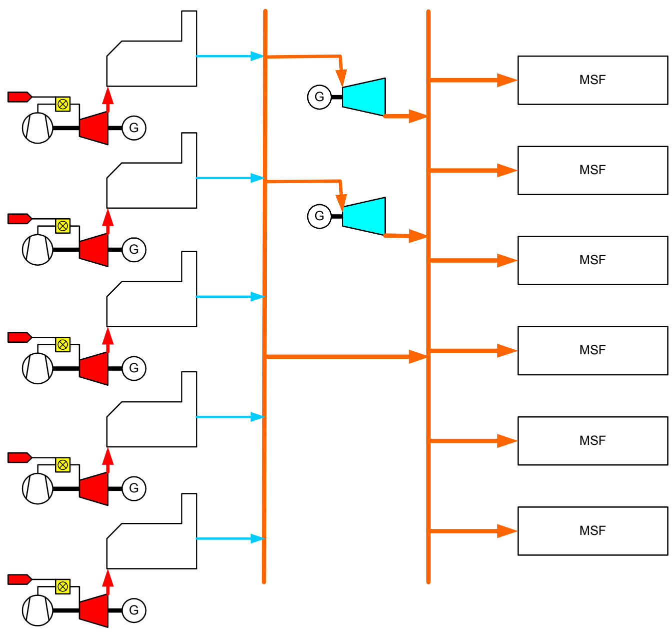

Figure 1 Typical cogeneration facility with gas turbines, heat-recovery steam boilers, back-pressure steam turbines, and multi-stage flash desalination units

Integrated Optimization

The implementation of an integrated, real-time optimization system requires hardware and software installed at a power plant. Figure 2 shows the basic building blocks of such an installation.

The software for an integrated optimization system consists of computer models to simulate plant performance. The models serve three tasks:

- Data Validation
- Performance Analysis
- Online Optimization

The full simulation of all parts of the plant, including the gas turbines, heat-recovery steam generators, steam turbines and the desalination plant, is essential for the success of the optimization system. That is why a number of integrated models, each serving a different purpose need to be developed. The following represents the models needed as part of an integrated optimization system:

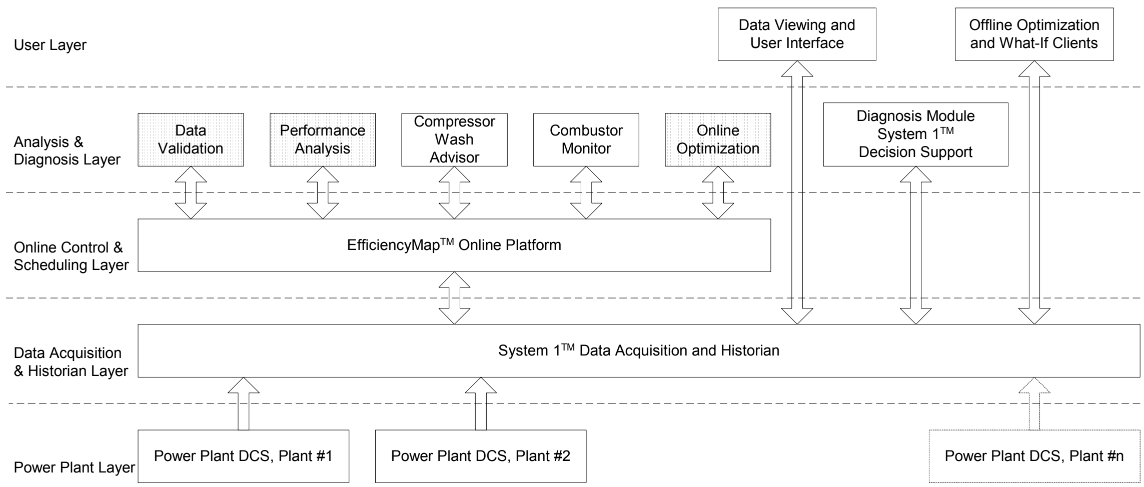

Figure 2 Conceptual overview of a computer based integrated optimization system

- Detailed thermodynamic simulation models:
    - Gas Turbine / Heat Recovery Boiler
    - Steam Turbine / Balance of Plant
    - Desalination Plant
- A parameterized thermo-economic optimization model

The detailed thermodynamic models are used to characterize the performance of the plant, taking into account the effects of part-load operation of all of the equipment. The models run on-line and continuously verify the measurements and calculate performance data. The system is designed to identify equipment degradation as it occurs over time. The calculated results are stored in a historical database for trending, analysis and reporting.

The other purpose of the thermodynamic model is to generate simplified performance equations, which constitute a key part of the thermo-economic optimization model. These simplified performance equations describe the impact of the controllable parameters on the overall plant performance. The equations must be simplified because of the large number of simulations required to carry out real-time optimization in an acceptable time frame.

Another set of equations needed to complete the thermo-economic optimization model describes the economic framework of the production facility. These equations take into account the fuel prices and revenues generated by the production of power and water. Together with the operating constraints, these equations are solved using a Mixed Integer Linear Programming (MILP) optimizer.

The results from the optimization runs can then be used by the plant operating staff to select the optimal settings for the plant controllable parameters.

Thermodynamic Modeling

Thermodynamic modeling is best accomplished using a power-plant simulation code such as General Electric's GateCycle™ software system. The simulation software has to provide mathematical models that can be executed in two modes: (1) design and (2) off-design. As described further below, when running in design mode the simulation software determines the design of the major equipment and the overall plant, and in off-design mode predicts plant performance under varying load and ambient conditions.

With a modular power-plant analysis tool, it is easy to quickly create models and analyze various plant configurations. The user selects unit operation icons from a build palette, arranges them on a graphical drawing page representing the basic plant layout, then draws the connecting steam, gas, and water lines to finalize the plant configuration.

Figure 3 shows a subset of the unit operation models available and a sample power plant model composed of selected unit operation icons.

The analysis code can be operated in two distinct modes: design mode and off design mode. In each mode, heat and mass balances are established.

In design mode, physical parameters of the various unit operations are determined. These include key characteristics such as heat exchange surface areas and steam turbine flow capacities.

In off-design or rating mode, the physical characteristics of the model are fixed to represent an "as-built" power plant. For example, the heat exchanger surfaces are kept fixed, and the heat transfer coefficients and pressure drops under varying operating conditions are calculated. Figure 4 shows an example of the off-design correlations used for a superheater. In this example, the coefficients are set to default values, but they can be adjusted as needed based on tests or measured data to exactly match the performance of the existing equipment over the entire load range.

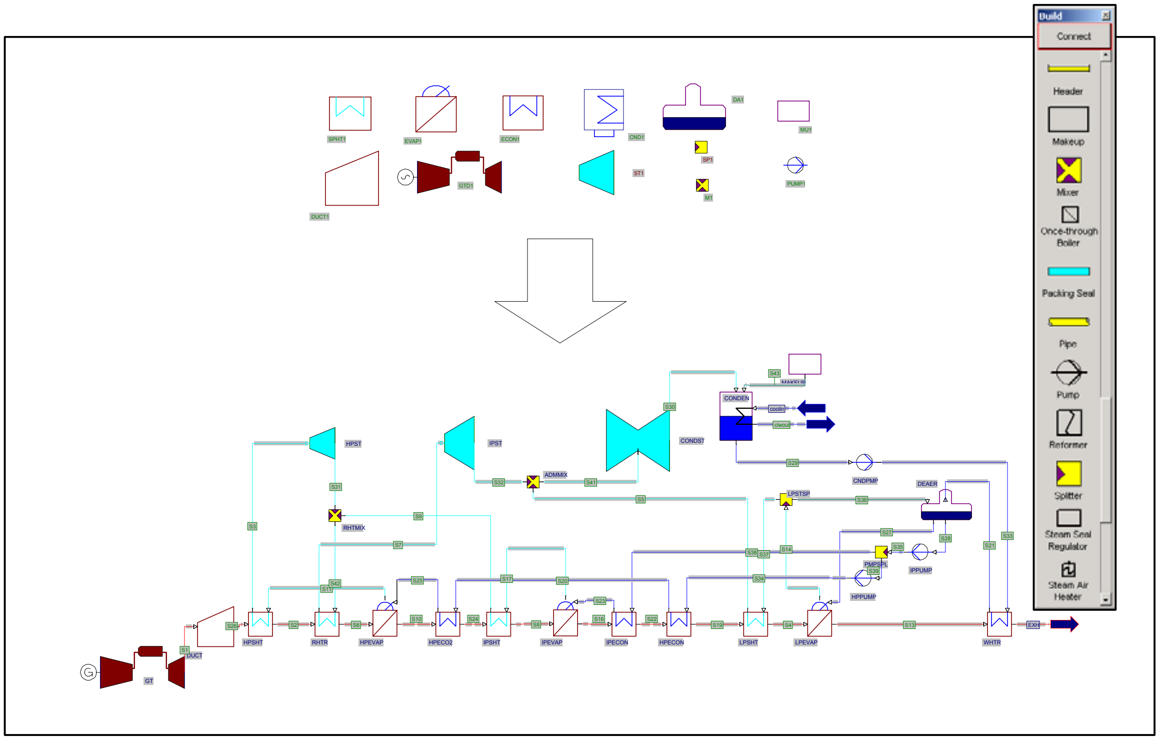

Figure 3: Concept of modular heat balance software

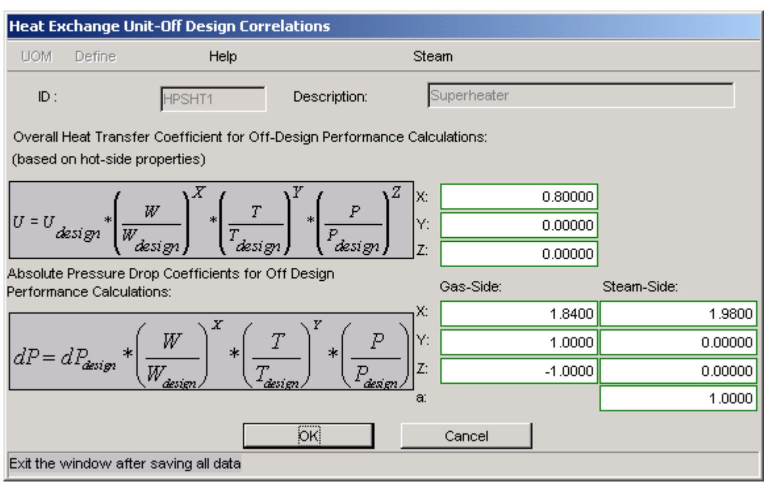

Figure 4: GateCycleTM Off-design Correlations Input Screen

Off-design operation of the steam turbine sections is calculated using a modified form of Stodola's law of the ellipse, using coefficients for flow capacity derived during the design case calculations. Utilizing the design and off-design modelling capabilities of the power-plant simulation software system and a detailed model constructed for the integrated power and desalination plant, the impact of changes in gas turbine exhaust gas on the overall steam cycle can be determined.

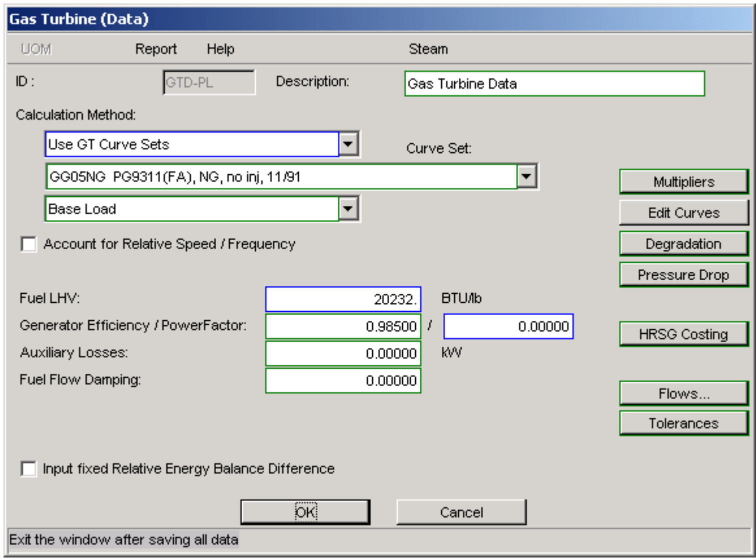

Figure 5: Data entry screen for gas turbine data

Gas Turbine Modeling

The study results presented below were carried out using a plant model that included a gas turbine unit operation model based on manufacturer's correction curves. With a correction-curve approach, the gas turbine base ratings are adjusted using a set of correction curves to determine the influence of the following key parameters:

- inlet temperature
- inlet pressure/altitude
- inlet pressure drop
- inlet relative humidity
- fuel LHV
- steam/water injection
- relative speed/frequency

The model automatically calculates the changes in the following results:

- gas turbine power output

- gas turbine heat rate
- exhaust gas mass flow
- exhaust gas temperature
- exhaust composition

The correction curves described above can be specified in tabular format, in order to exactly represent manufacturer's engine data.

In addition, part-load operation of the gas turbine can be modelled by including additional tables representing correction factors for heat rate, exhaust gas temperature and flow as a function of part-load fraction.

The correction factors derived from the above-mentioned tables are applied to the gas turbine base rating. As a special feature, the Data Gas Turbine unit operation model calculates the overall energy balance around the gas turbine, which enables a user to adjust one of the output values, derived from the curve sets, in order to close the gas turbine energy balance.

Combined Power and Desalination Modeling

A model was generated for an integrated power and desalination plant of the configuration shown in Figure 1. The plant consists of five gas turbines of the GE 9FA class, each with a single-pressure heat-recovery steam generator. The steam is collected in one HP steam header then fed into two back-pressure steam turbines, each about 250 MW in size. The exiting backpressure steam is controlled to about 2.7 bar and collected in a low-pressure steam header. This header delivers 2.7 bar steam to six desalination units, each with an approximate capacity of about 12 MIGD.

To represent such a plant, three separate models were created:

- Gas turbine and heat recovery train
- Steam Turbine and balance of plant
- Desalination model

As shown in Figure 6, the gas turbine and heat-recovery train model includes the major equipment in these sections of the plant, namely the gas turbine and the heat-recovery steam generator, which is comprised of economizer, evaporator, superheaters and a spray cooler.

As shown in Figure 7, the steam turbine and balance-of-plant model is used to determine the steam turbine performance, and in addition to the steam turbines includes all steam, boiler-feedwater, condensate and fresh water headers. To simplify the balance-of-plant modeling, the collective steam demand for the desalination units is represented by a single heat sink.

A detailed desalination model has been set up to model all of the individual flash stages. Figure 8 shows the level of detail included in the model. Seawater properties are used and the impact of salinity on the vapor pressure is taken into account.

Modeling Procedure

The various models are connected using special sink and source icon links to automatically transfer calculated process stream data from one heat balance sub-model to the others. An overall run control routine calls the three sub-models which comprise the integrated power and desalination plant model in a consecutive manner until overall system convergence is achieved.

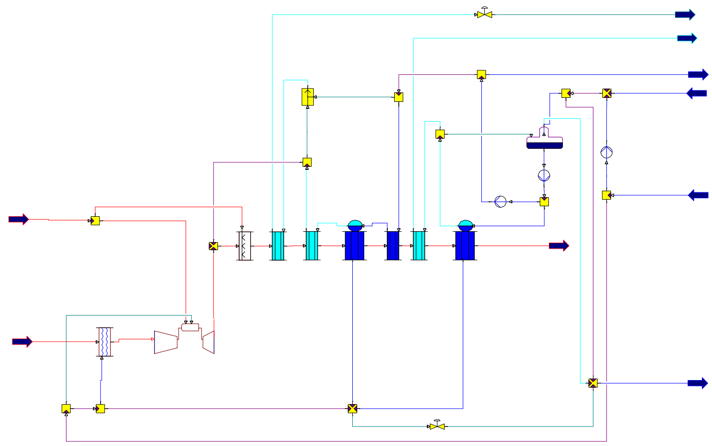

Figure 6: The simulation model for a single representative gas-turbine heat-recovery train.

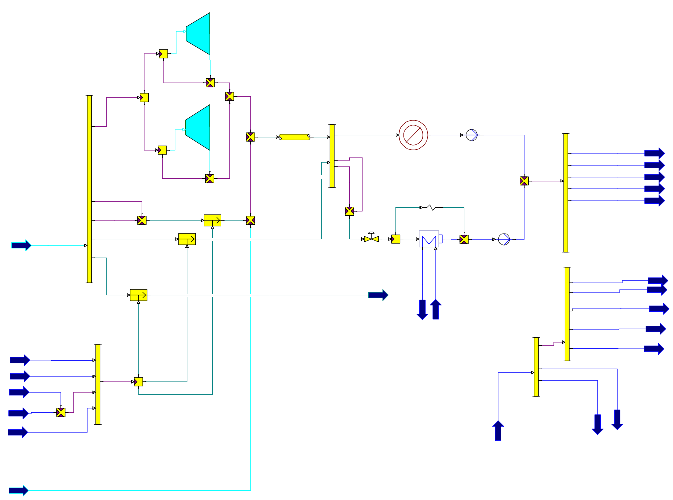

Figure 7 The simulation model for the steam turbines and balance of plant.

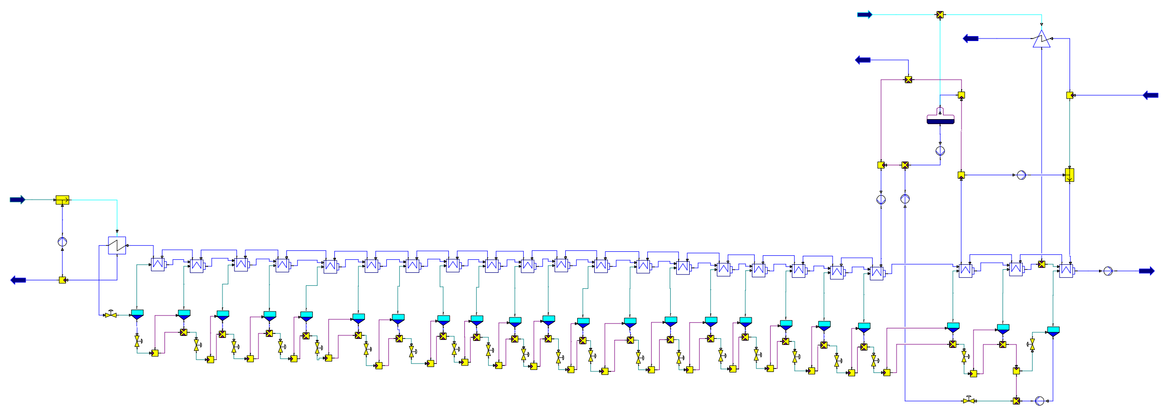

Figure 8: Detailed simulation model for an MSF desalination plant.

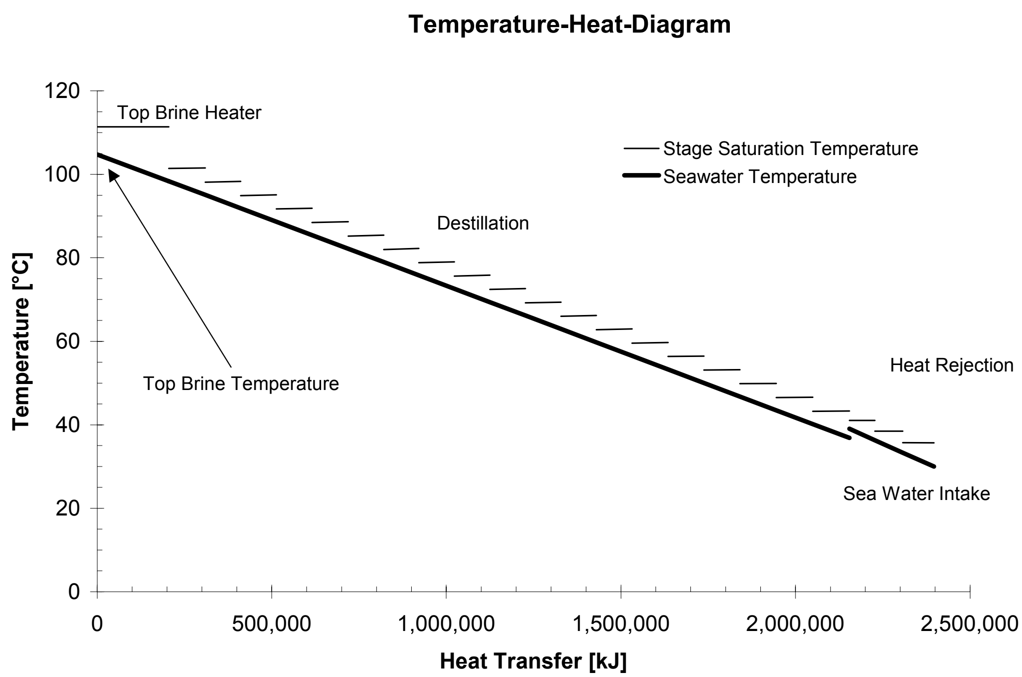

Figure 9: Temperature-Heat Profile of a typical MSF desalination plant.

Modeling Assumptions

The purpose of the overall integrated system model is to mimic the physical behavior of the overall plant. General data taken from the open literature were used to configure the performance models for the gas and steam turbines, as well as the desalination plant. No specific vendor data were used except for the gas turbine, for which representative data for the GE 9FA technology gas turbine was used. The following assumptions were made:

Gas Turbine Data:

The model assumed typical performance for a GE 9FA type gas turbine as originally published in 1998. No conclusion should be drawn from this data concerning the performance of current or specific GE 9FA gas turbines: the reader is asked to contact GE directly for the latest relevant performance data.

At ISO conditions, it was assumed the gas turbine can deliver 226.5 MW with a heat rate of 9570 BTU/kWh, an exhaust temperature of 1096°F, and an exhaust flow of 4,877,000 lb/hr.

Steam Turbine Data:

The general steam turbine icon model in the GateCycle™ software system was used to estimate the design and off-design performance of the steam turbines. At maximum continuous rating for the selected design conditions, each steam turbine was estimated to deliver about 270 MW, at 90 bar /560°C inlet condition and a backpressure of 2.7 bar.

Desalination Plant:

For the desalination plant, the unit size was assumed to be about 12.5 MIGD. The equipment was designed assuming a TTD of 3-4°C per stage and a TTD of about 7-8°C at the top brine heater. The blowdown ratio was assumed to be 12% of the brine flow through the distiller section. Figure 9 shows the temperature heat profile calculated for the MSF simulation model.

Model Results

The data presented here is included for illustrative purposes only, and is not related to any specific or known facility. Table 1 presents the calculated overall plant performance at conditions representative of typical summer, autumn, spring and winter days (cases 1, 2, 3 and 4 respectively). The simulation runs were made assuming full nominal water output and typical dispatch levels for the power.

The results of simulation runs for three different operating scenarios are presented in Figures 10, 11 and 12. Figure 10 shows the dependence of the overall plant heat rate on the load distribution between the gas turbines and the steam turbines at 70 and 90% nominal plant power output. Figure 11 shows the same relationship at two different ambient temperatures, and Figure 12 shows the impact of seawater temperature.

The operation of such an integrated power and desalination plant offers some freedom in selecting how to set the controllable parameters for the gas turbine load, steam turbine load, duct firing levels and steam let-downs. The simulation runs show distinct minima of plant heat rate as the controllable parameters are varied over typical ranges. As can be seen from the diagrams, these minima are at different locations for the varying scenarios.

		Case 1	Case 2	Case 3	Case 4
Configuration					
# GT/HRSG		5	5	5	5
# ST's		2	2	2	2
# Desalination Units		6	6	6	6
Net Electrical Output	%	100%	80%	70%	50%
Gross Fresh Water Output	%	100%	100%	100%	100%
Ambient Conditions					
Ambient Air Temperature	°C	35.00	34.00	30.00	22.00
Ambient Air Relative Humidity	%	0.70	0.70	0.70	0.70
Sea Water Temperature	°C	35.00	32.00	30.00	22.00
Gross Power Output					
Gross Gas Turbine Power	kW	1,127,571	908,607	782,522	491,930
Gross Steam Turbine Power	kW	429,367	358,477	339,867	340,300
Total	kW	1,556,939	1,267,084	1,122,389	832,230
DESAL Performance					
DESAL Performance Ratio		9.98	9.98	9.98	9.98
Top Brine Temperature	°C	107.50	107.51	107.51	107.52
Top Brine Heater Shell Pressure	bar	1.65	1.65	1.65	1.65
Net Water Production					
	kg/s	5,184.37	5,185.72	5,184.67	5,185.51
	m^3/day	447,929	448,046	447,955	448,028
	MIGD	99.31	99.33	99.31	99.33
Plant Output					
Gross Plant Output	kW	1,556,939	1,267,084	1,122,389	832,230
Auxiliary Power Consumption	kW	120,103	117,619	116,635	113,829
Net Plant Output	kW	1,436,836	1,149,466	1,005,755	718,401
Plant Fuel Consumption	kW	3,542,494	2,984,521	2,777,741	2,389,860
Gross Plant Heat Rate	kJ/kWh	8,191	8,480	8,909	10,338
Gross Plant Efficiency	%	43.95%	42.46%	40.41%	34.82%
Net Plant Heat Rate	kJ/kWh	8,876	9,347	9,943	11,976
Net Plant Efficiency	%	40.56%	38.51%	36.21%	30.06%

Table 1: Performance data for typical days for each season throughout the year.

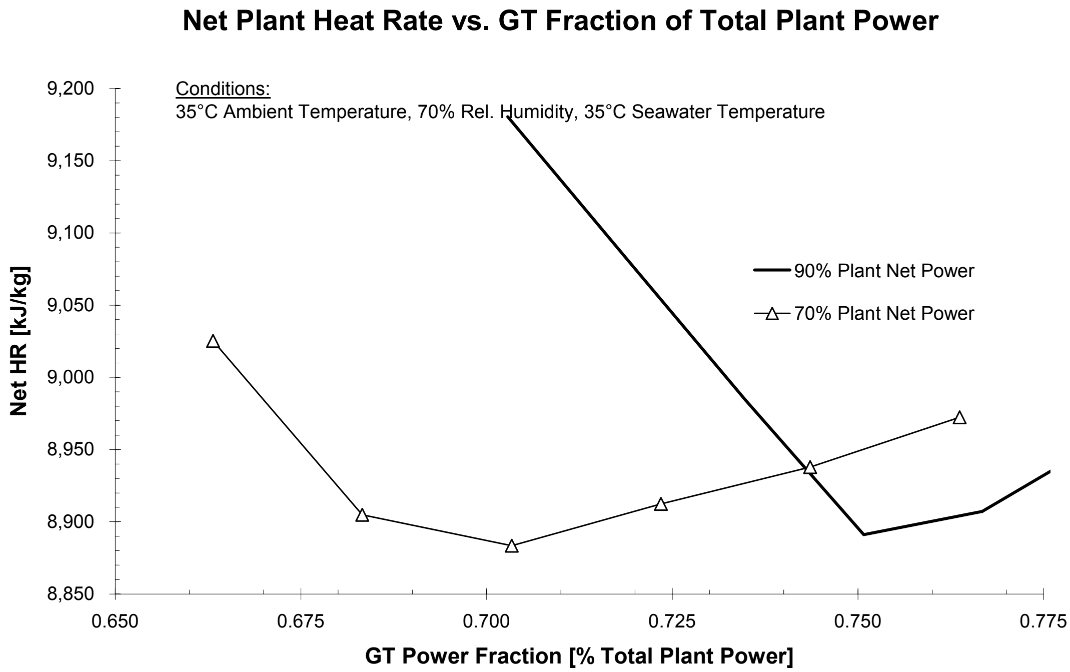

Figure 10: Net heat rate as a function of the load distribution between the gas turbines and the steam turbines and the total plant load.

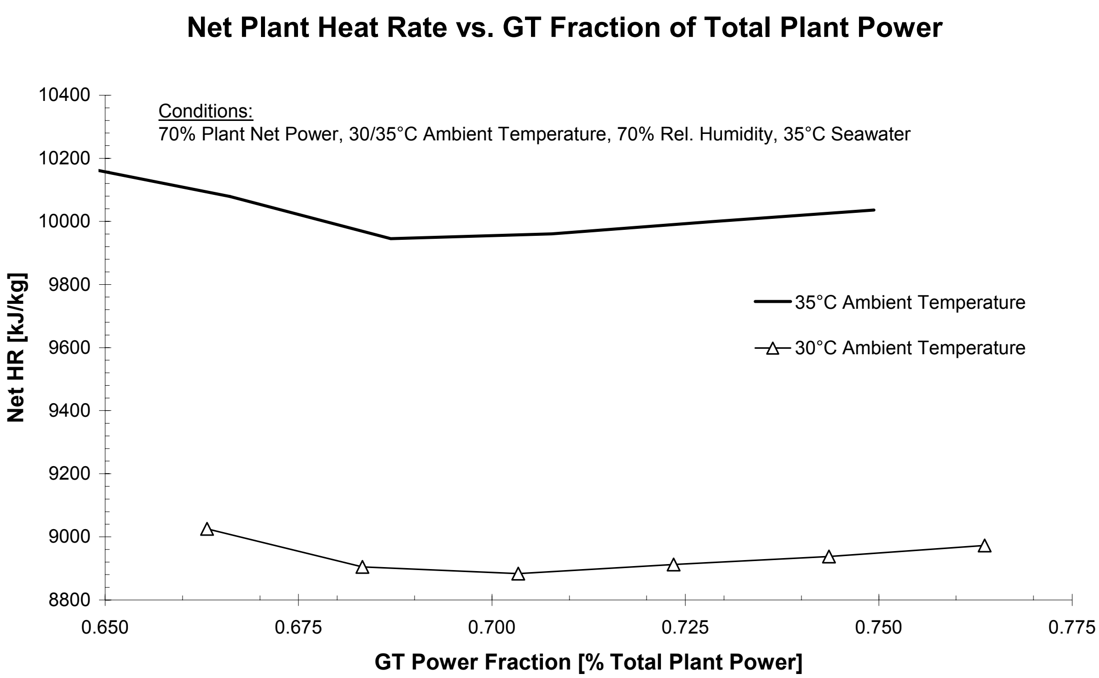

Figure 11: Net heat rate as a function of the load distribution between the gas turbines and the steam turbines and the ambient temperature.

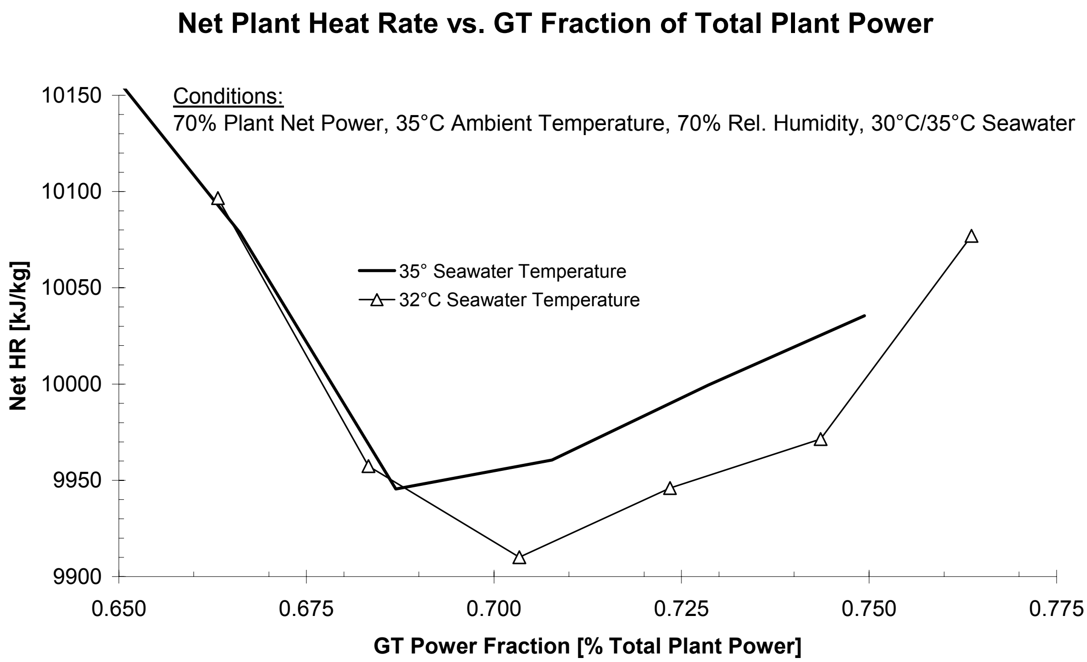

Figure 12: Net heat rate as a function of the load distribution between the gas turbines and the steam turbines and the seawater temperature.

A real-time integrated optimization system takes all of these parameters fully into account at each optimization run. In addition to load and ambient conditions, other parameters also must be taken into account for true optimization. These parameters include degradation factors for key plant equipment. The on-line performance monitoring system will determine current equipment degradation parameters automatically and make these available for simulation and optimization runs through the historical database. The on-line optimizer will pick these up at each run and tune its performance model to take into account the current health of the equipment.

Thermo-Economic Optimization

The on-line optimization software incorporates mathematical models for power plant performance, as well as models for the economic revenue and cost streams associated with plant operation. One result of the optimization calculations is therefore the operating mode of the plant that maximizes the profit of the generation, subject to all of the constraints imposed by the desalination plant, the operators, and the equipment limitations. In typical installations of such a software optimization system, the software recommends to the plant operators the optimal set points for the plant equipment in order to satisfy the plant net power and desalination steam demands.

Thermo-economic optimization considers all of the following: the thermal performance characteristics of the power plant equipment; how these pieces of equipment interact to produce overall plant performance; and the economic consequences of the resulting plant operation. This detailed analysis predicts the set points of plant equipment that maximize plant operational profits while meeting all operational constraints.

The primary controllable parameters are the power level set points of the five gas turbines and the two steam turbines, as well as the duct burner firing rates. The optimization of these power level set points is a factor in plant economics only when such a plant is part-loaded. During full-load power plant operation, all engines are set to baseload operating conditions, and there are no significant controllable parameters to analyze with the optimization system. However, as discussed above, such combined power-and-water facilities run at full water production levels but at part-load power production levels more than 50% of the time. During these times, the described thermo-economic optimization calculations may provide significant benefits to the plant operation.

Another important factor affecting the operating profit of integrated power and desalination plants is the ratio of fuel price to electricity price. The lower this ratio, the more important is the effect of key variables on plant profit.

The optimal allocation of plant load to the five gas turbines depends upon many factors, including the relative ratings or degradation of the engines. Normally one would assume it is best to run the most efficient engines at the higher loads; however, in situations where there is too much power production and duct burners are needed to provide full steam output, it actually makes sense to consider firing the less-efficient gas turbine before the highest efficiency ones.

A difficulty arises from the fact that due to compressor fouling and cleaning, the difference between the two engines varies over time. Thus, the optimal load allocation varies over time. To be accurate, a thermo-economic optimization tool must be able to identify and take into account these variations in equipment performance and degradation. Another publication ("Benefits of Optimization", a white paper of General Electric, available upon request from the author) indicates potential savings of two to five percent of the fuel consumption, for a multi train plant of identical gas turbines, operating at different levels of degradation.

Thermal Model

The accurate thermodynamic models described previously serve as references to create simplified, parameterized mathematical equations that are used in the optimizer engine.

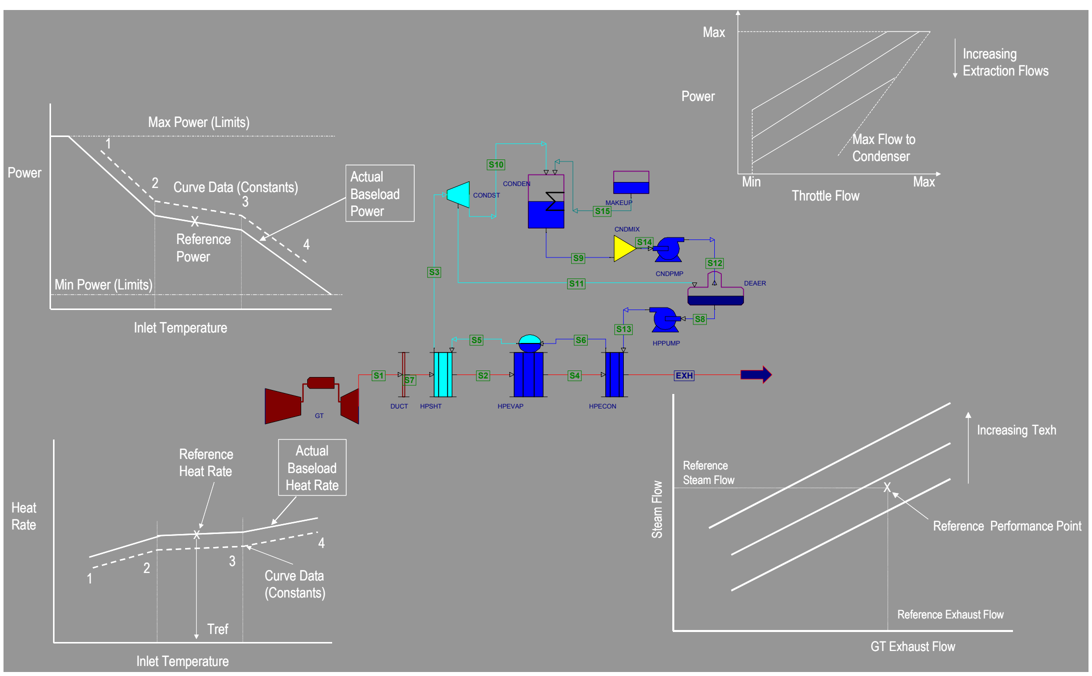

Figure 12: Parameterized models of power plant equipment for optimization

Economic Model

The on-line optimizer model considers plant revenues and expenses, and then predicts the plant operating condition that maximizes the operational profit. The user may input purchase prices for fuel and chemicals, and sales prices for electricity, gas fuel and drinking water. The model optionally supports several electricity or water customers, each with separate contracts and price levels. Each contract stipulation is modeled by simply specifying a price and maximum and minimum quantities, including a fixed generation quantity if so desired. Each of the revenue and expense streams may be modeled by inputting contract stipulations.

Variable maintenance costs are input as hourly costs associated with operation of gas turbines, steam turbines and auxiliary boilers. Peak firing of the gas turbines increases the maintenance costs through a user input for cost per MW-hr of over-firing.

Revenues
Sales of Electricity
Sales of Water
Expenses
Cost of Fuel
Cost of Chemicals
Variable Maintenance Costs
Fixed Costs

Table 2: Revenue and Cost Inputs to an Optimizer Model

Operational Limits

Key elements, which must be included in optimization modeling, are the specification of operational or permit limits. These limits are mathematical constraints for the key optimization variables, which constrain the optimization solution such that it does not suggest unacceptable operational modes where the plant operator cannot or may not actually run the plant. For example, the maximum gas turbine power may be set by limits on the generator, or the minimum power level may reflect an environmental constraint imposed by a regulatory body. The on-line optimizer model accepts maximum and minimum constraints for most of the heat balance values calculated by the software.

Output

The optimizer model, tuned to reflect the current equipment health, solves the overall plant process model equations to maximize the net income objective function:

Net Income = ∑Electricity sold + ∑Drinking water sold
- ∑Fuel purchased - ∑Electricity purchased - ∑Equipment maintenance costs - ∑Plant fixed costs -∑Chemicals

The optimizer software determines the optimal distribution of power generated by each turbine, steam production by each boiler, and fuel flows to all equipment. The solution provided by the solver is always a global optimum. These values are sent to the plant's data archive, and are also shown in a suitable graphical user interface. Operators may elect to run their plant according to these advisory set points, thereby increasing their operating profit.

Conclusions

Engineering software tools exist which can accurately model the key equipment and overall system performance of integrated power and desalination facilities. These tools can be extended to evaluate and optimize plant economics under all operating conditions.

An illustrative model of an integrated power and desalination plant was developed based on current state-of-the-art equipment specifications. An initial set of simulation and optimization runs were made using this example model to study typical plant performance and to evaluate potential operating scenarios in order to reduce cost or improve performance. These initial runs indicate that the optimal strategy for regulating the steam supply of the desalination units is to control the flow to the steam turbine so it is just equal to the amount of steam required by the desalination units. There is an opportunity to optimize plant performance in real time, using the on-line performance and optimization software system described here to guide the plant operating staff in the loading and unloading of the gas turbines, particularly when the plant is operating at part load and the gas turbines are exhibiting unequal degradation.

Additional studies are suggested to evaluate alternative design and operating strategies and to further quantify the potential savings for an integrated power-and-water facility.