Renewable Energy Based Tri-Generation Scheduling Model for an Industrial Center

Secil Ercan and Gulgun Kayakutlu

***Abstract*—Hybrid energy resources are generally accepted with the concern of global pollution and warming. Optimization studies on the detailed scheduling of hybrid energy usage are trying to find solutions for complex problems including uncertainty and lots of data. This paper gives the comparison of applying a MIP model and a stochastic model for detailed scheduling of a tri-generation system using wind and solar sources with thermal collectors. The proposed hourly scheduling will allow balancing the production and consumption as well as giving more realistic commitments the day ahead. The model is applied and compared for regional energy production to respond the demands of an industrial center in Turkey.**

***Index Terms*—Scheduling, stochastic model, tri-generation, CCHP, solar energy, wind energy.**

I. Introduction

Operational optimization for the energy systems are focused on load optimization, demand site management, life long cost minimization. Scheduling is one of the most encountered short-term operational problems, but was not an interest for energy generation with fuel or gas turbines run for 7 days 24 hours. Advanced scheduling of energy production is a rising need for integrated use of hybrid renewable energy resources.

This study is based on [1], where authors presented a new stochastic model for detailed scheduling of a renewable trigeneration system with uncertainties. The MIP model and the stochastic model are used for a sample system designed to include a wind turbine, the solar photovoltaic panels and thermal collectors for the use of an industrial center with several manufacturing plants. In the deterministic model some limits were assumed but the uncertainties in electricity price, energy demand, and output of renewable resources caused the construction of a complex problem, where, the problems are handled with application of the stochastic model.

The paper is so organized that, a literature review of scheduling studies on renewable energy resources is summarized in the next section. Section 3 will give a brief definition of CCHP systems and the proposed system. Then, Section 4 will be devoted to proposed models in detail. Section 5 will summarize the application and comparisons. Finally, the concluding remarks will be given in the last section.

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II. Literature Review

Scheduling of the energy systems concerns operational strategies. The scheduling problem should provide the balance of energy production and consumption because energy consumption is as important as energy production.

Renewable energy systems have lots of potential advantages on especially environment; however suitable scheduling strategies must be constituted in order to exploit these advantages.

There are several studies that consider the renewable energy systems, combined heating and power (CHP) energy systems, or both of renewable and CHP systems. Scheduling of renewable energy systems is mostly studied. Many of these studies consider the uncertainty of wind or solar energy systems.

Many studies generally prefer to optimize the **wind energy system** Two-stage stochastic programming method is widely applied for wind energy systems [2-6] in order to minimize the cost or maximize the profit. Ref [7] and Ref [8] used stochastic programming with scenario analysis to schedule the energy system based on wind energy. Ref [9] also considered the uncertainty of wind energy and implemented mixed-integer linear programming. Ref [10] applied Monte Carlo simulation and mixed-integer linear programming to solve the unit commitment problem for a wind-based energy system. In another wind-based system study, neural networks were used to maximize the daily revenue [11].

A few studies also optimized the schedule of **wind-solar energy systems.** Ref [12] solved the storage scheduling problem and Ref [13] solved the production scheduling problem by mixed-integer linear programming for a hybrid renewable energy system. To handle with the uncertainty of a wind-solar energy system, Ref [14] implemented fuzzy optimization where Ref [15] employed two-stage stochastic programming. Ref [16] minimized cost and emission by particle swarm optimization. Ref [17] applied Markov decision process for storage scheduling.

Previous studies investigate the energy systems that only produce electricity. There are a few studies that consider **CHP systems** based on **wind** or **solar** or **wind-solar hybrid** energy systems. Ref [18] implemented mixed-integer programming for multi objective optimization and utilized fuzzy decision making whereas Ref [19] applied bi-population chaotic differential evolution algorithm for a **wind**-based CHP system. Ref [20] used mixed integer programming and Ref [21] applied auto-regressive moving average, time series model and stochastic mixed integer programming for a **solar**-based CHP system. Ref [22] modeled **wind energy and photovoltaic** as a stochastic

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model in detail. The electricity and thermal power production were scheduled by hybridizing artificial neural network with genetic algorithm and a priority list. Ref [23] proposed an enhanced cuckoo optimization algorithm for a **wind-solar hybrid** system that produces both of electricity and heating by focusing on energy storage systems.

It is observed that there are not many studies on scheduling of trigeneration energy systems. An example for scheduling of a solar-based CCHP system which uses PV model is proposed by Ref [24].

III. CCHP System

Trigeneration systems produce three types of energy, simultaneously. These systems utilize waste heat which gets out while producing electricity. The most known form of trigeneration is combined cooling, heating and power systems which is called as CCHP. CCHP is a decentralized energy system which does not depend on a central system. Therefore, transmission losses and any interruptions are less than the traditional energy systems. Production point is close to consumption point. CCHP is generally fed by natural gas based power generation units such as boilers, gas engines, gas turbines, Stirling engines, fuel cells [25].

The main power generation units produce the electricity and heating as is the case with CHP. The difference from CHP is converting the electricity and heating to cooling by using electrical chiller and absorption chiller or adsorption chiller. A typical CCHP system is shown in Fig. 1.

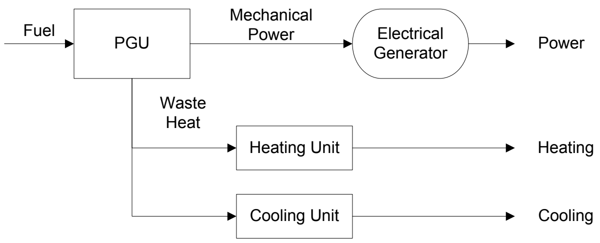

Fig. 1. A typical CCHP system.

This study considers a trigeneration energy system that mainly utilized wind and solar energy (shown in Fig. 2). When wind and solar energy are not enough, electric will be purchased form the grid or natural gas. Photovoltaic (PV) systems and solar thermal collectors will take place in the system by utilizing the solar. PV units only produce electricity while solar thermal collectors can produce both of electricity and heating.

The system tries to satisfy the demand of electricity and heating from directly auto-production or grid. For industrial systems, industrial outputs such as steam will also support the heating output. Remaining part of the production is stored in the battery and thermal storage devices. Since outputs of wind and solar energy are fluctuated, electricity prices and power demands are uncertain, storage has a significant role. Battery and thermal storage devices not only meet the following period's electricity and heating demand but also provide the electricity and heating to the electrical and absorption chiller in order to convert them to cooling.

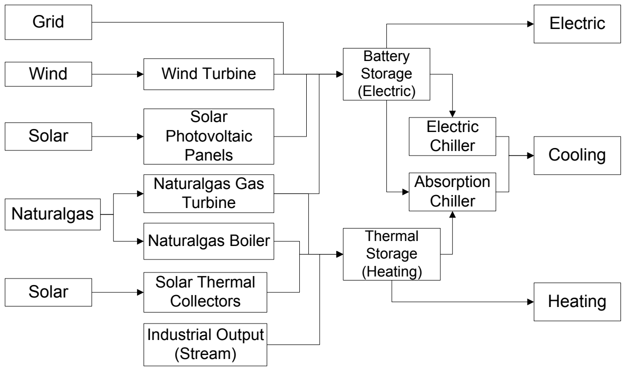

Fig. 2. The proposed CCHP system.

IV. System Modelling

Both the MIP and stochastic models will use the nomenclature given in Table I.

The objective of the MIP model is to minimize the total production and stock costs. Since the production and consumption of the energy is hourly scheduled, total cost function is equal to the sum of hourly costs. Table 2 displays the cost items for hour t. Since gas turbine provides both electricity and heating, the production costs depend on efficiencies. When efficiency increases, unit cost decreases.

We want to minimize the daily costs. Thus, the objective function is the sum of these cost items over 24 hours.

$$\min \sum_{t=1}^{24}(\beta_{G,t}E_{G,t} + \beta_{GT,t}E_{GT,t} + \beta_{WT,t}E_{WT,t} + \beta_{PV,t}E_{PV,t})$$
$$+\sum_{t=1}^{24}(\beta_{GT,t}Q_{GT,t} + \beta_{B,t}Q_{B,t} + \beta_{TC,t}Q_{TC,t} + \beta_{S,t}Q_{S,t})$$
$$+\sum_{t=1}^{24}(\theta_{et}s_{et} + \theta_{qt}s_{qt}) + \sum_{t=1}^{24}(\gamma_{et}R_{et} + \gamma_{qt}R_{qt}) \qquad (1)$$

TABLE I: Nomenclature of Subscripts, Decision Variables, and Parameters

Subscripts	
G	Grid
GT	Gas turbine
WT	Wind turbine
PV	Photovoltaic
B	Boiler
TC	Thermal collector
S	Steam
e	Electricity
q	Heating
r	Cooling (refrigeration)
t	Time (hour)
AC	Absorption chiller
EC	Electric chiller
Decision variables	
$E_{G,t}$	Amount of electricity imported from the grid in hour *t*
$E_{GT,t}$	Amount of electricity produced by naturalgas gas turbine in hour *t*
$E_{WT,t}$	Amount of electricity produced by wind turbine in hour *t*
$E_{PV,t}$	Amount of electricity produced by photovoltaic panels in hour *t*
$Q_{GT,t}$	Amount of heating produced by naturalgas gas turbine in hour *t*
$Q_{B,t}$	Amount of heating produced by naturalgas boiler in hour *t*

$Q_{TC,t}$	Amount of heating produced by thermal collectors in hour *t*
$Q_{S,t}$	Amount of heating produced by steam as an industrial output in hour *t*
s_{et}	Amount of storage for electricity in hour *t*
s_{qt}	Amount of storage for heating in hour *t*
R_{et}	Amount of cooling (refrigeration) produced by utilizing electricity in hour *t*
R_{qt}	Amount of cooling (refrigeration) produced by utilizing heating in hour *t*
E_{rt}	Electricity required by electric chiller to produce cooling in hour *t*
Q_{rt}	Heating required by electric chiller to produce cooling in hour *t*
Parameters	
$\beta_{.,t}$	Coefficient of production or purchasing cost in hour *t* (for G, GT, WT, PV, B, TC, S)
η_e, η_h	Efficiency of gas turbine for electricity and heating, respectively
θ_{et}, θ_{qt}	Coefficient of storage cost in hour *t* for electricity and heating, respectively
γ_{et}, γ_{qt}	Coefficient of cost for producing cooling in hour *t* (for electricity and heating, respectively)
d_{et}, d_{qt}, d_{rt}	Demand amount in hour *t* for electricity, heating and cooling, respectively
$\rho_{.t}$	Coefficient of gas emission
c_{et}, c_{qt}	Capacity of storage in hour *t* for electricity and heating, respectively
$\lambda_{.,t}$	Production capacity in hour *t* (for G, GT, B, S)
K	Allowable maximum CO_2 emission
COP_{EC}	Coefficient of performance for electric chiller (EC)
COP_{AC}	Coefficient of performance for absorption chiller (AC)

Energy balance constraints: Electric (power), heating and cooling demands must be satisfied by that period's production and previous period's storage. After the satisfaction of the demands, remaining is hold in battery and thermal storage.

Power balance

$$E_{G,t} + E_{GT,t} + E_{WT,t} + E_{PV,t} + s_{et} - d_{et} - E_{rt} - s_{e,t+1} = 0, \ \forall t \tag{2}$$

Heat balance

$$Q_{GT,t} + Q_{B,t} + Q_{TC,t} + Q_{S,t} + s_{qt} - d_{qt} - Q_{rt} - s_{q,t+1} = 0, \ \forall t \tag{3}$$

Cooling balance

$$R_{et} + R_{qt} - d_{rt} = 0, \ \forall t \tag{4}$$

TABLE II: Cost Items for an Hour

Cost item	Formula
Electricity production cost	$\beta_{G,t}E_{G,t} + (\beta_{GT,t}/\eta_e)E_{GT,t} + \beta_{WT,t}E_{WT,t} + \beta_{PV,t}E_{PV,t}$
Heating production cost	$(\beta_{GT,t}/\eta_h)Q_{GT,t} + \beta_{B,t}Q_{B,t} + \beta_{TC,t}Q_{TC,t} + \beta_{S,t}Q_{S,t}$
Storage cost	$\theta_{et}s_{et} + \theta_{qt}s_{qt}$
Cooling production cost	$\gamma_{et}R_{et} + \gamma_{qt}R_{qt}$

Storage capacity constraints (battery and thermal storage devices): Electricity and heating are stored as energy not power. The capacities are based on chosen battery and thermal storage device.

$$s_{et} \le c_{et}, \ \forall t \tag{5}$$

$$s_{qt} \le c_{qt}, \ \forall t \tag{6}$$

Production_capacity constraints:

Capacity for **wind turbine** is based on the probability density function of wind speed.

$$E_{WT,t} \le f_{WT}(v), \ \forall t \tag{7}$$

where *v* denotes wind speed. Since wind speed is uncertain, we consider its distribution as empirical distribution.

The amount of solar irradiance affects the capacity for **PV panels** and **thermal collectors**. Both of them are based on solar irradiance (*I*) with different functions.

$$E_{PV,t} \le f_{PV}(I), \ \forall t \tag{8}$$

$$Q_{TC,t} \le f_{TC}(I), \ \forall t \tag{9}$$

Natural gas boiler and **natural gas turbine** capacities do not change after the design of the system. On the other hand, capacities of gas turbine for electricity and for heating depend on their efficiencies. If efficiency is high, then there is more capacity for that energy type.

$$Q_{B,t} \le \lambda_{B,t}, \ \forall t \tag{10}$$

$$E_{GT,t} \le \eta_e \lambda_{GT,t}, \ \forall t \tag{11}$$

$$Q_{GT,t} \le \eta_h \lambda_{GT,t}, \ \forall t \tag{12}$$

There is also an upper limit for purchasing electricity from **grid**.

$$E_{G,t} \le \lambda_{G,t}, \ \forall t \tag{13}$$

CO_2 emission: Environmental impact of gas emissions is another significant fact that must be considered. Since CO_2 emission causes global warming, total emission should be restricted by an upper bound.

$$\sum_{t=1}^{24}(\rho_{G,t}E_{G,t} + \rho_{GT,t}E_{GT,t} + \rho_{WT,t}E_{WT,t} + \rho_{PV,t}E_{PV,t}) + \sum_{t=1}^{24}(\rho_{GT,t}Q_{GT,t} + \rho_{B,t}Q_{B,t} + \rho_{TC,t}Q_{TC,t} + \rho_{S,t}Q_{S,t}) \le K \tag{14}$$

Energy equations: In addition to these constraints, there are a few equations about energy transformation, availability.

Cooling by the chillers cannot be directly transformed as imported electricity and heating. Amount of produced cooling is calculated by multiplying the required electricity and heating with coefficient of performance (COP) which describes efficiencies of chillers.

$$R_{et} = E_{rt} COP_{EC} \ , \ \forall t \tag{15}$$

$$R_{qt} = Q_{rt} COP_{AC} \ , \ \forall t \tag{16}$$

Since cooling is produced by electricity and heating imported from storages, imported electricity and heating should not exceed the amount in storages.

$$E_{rt} \le s_{et} \ , \ \forall t \tag{17}$$

$$Q_{rt} \le s_{qt} \ , \ \forall t \tag{18}$$

Stochastic programming is used to handle the uncertainties detected during the simulation of the model. Uncertainty may be in constraints or in any coefficient of objective function.

Let $A(x)$ be the event that is desired to realize where Z is the random vector that includes uncertainty.

$$A(x) = \{ g_j(x, Z) \le 0 \} \tag{19}$$

Then, in stochastic programming, probabilistic constraint for event $A(x)$ is formulated as in the following [26].

$$\Pr\{A(x)\} \ge p \Rightarrow \quad \Pr\{g_j(x, Z) \le 0\} \ge p \tag{20}$$

p has values in a range between 0 and 1.

If the uncertainty is in the objective function, the objective becomes to minimize (or maximize) the expected value of the objective function.

$$\min \sum_t E[c_t x_t] \tag{21}$$

$$E[X] = \sum_k p_k x_k \Rightarrow \quad \min \sum_t \sum_k p_k (c_t^k x_t) \tag{22}$$

where the sum of p_k's is 1, and c^k denotes different scenarios for the coefficient of objective function.

In this study,

- Electricity price
- Demand for electricity, heating, and cooling
- Output of wind and solar energy

have uncertain properties.

Let p_k be the probability for electricity price, p_e be the probability for electricity demand, p_h be the probability for heating demand, p_r be the probability for cooling demand, p_v be the probability for wind speed, p_I be the probability for solar irradiance. Then, stochastic constraints are the following:

$$\Pr\{E_{G,t} + E_{GT,t} + E_{WT,t} + E_{PV,t} + s_{et} - d_{et} - E_{rt} - s_{e,t+1} = 0\} \ge p_e$$

$$\Pr\{Q_{GT,t} + Q_{B,t} + Q_{TC,t} + Q_{S,t} + s_{qt} - d_{qt} - Q_{rt} - s_{q,t+1} = 0\} \ge p_q$$

$$\Pr\{R_{et} + R_{qt} - d_{rt} = 0\} \ge p_r$$

$$s_{et} \le c_{et}$$

$$s_{qt} \le c_{qt}$$

$$\Pr\{E_{WT,t} \le f_{WT}(v)\} \ge p_v$$

$$\Pr\{E_{PV,t} \le f_{PV}(I)\} \ge p_I$$

$$\Pr\{Q_{TC,t} \le f_{TC}(I)\} \ge p_I$$

$$Q_{B,t} \le \lambda_{B,t}$$

$$E_{GT,t} \le \eta_e \lambda_{GT,t}$$

$$Q_{GT,t} \le \eta_h \lambda_{GT,t}$$

$$E_{G,t} \le \lambda_{G,t} \ , \ \forall t$$

$$\sum_{t=1}^{24} (\rho_{G,t} E_{G,t} + \rho_{GT,t} E_{GT,t} + \rho_{WT,t} E_{WT,t} + \rho_{PV,t} E_{PV,t})$$
$$+ \sum_{t=1}^{24} (\rho_{GT,t} Q_{GT,t} + \rho_{B,t} Q_{B,t} + \rho_{TC,t} Q_{TC,t} + \rho_{S,t} Q_{S,t}) \le K$$

$$R_{et} = E_{rt} COP_{EC}$$

$$R_{qt} = Q_{rt} COP_{AC}$$

$$E_{rt} \le s_{et}$$

$$Q_{rt} \le s_{qt}$$

All variables are nonnegative

All constraints are for all $t = 1, 2, \ldots, 24$

V. Application and Comparisons

Case study is run for Gebze Industrial center where 723,000 MWh of power, 221,000 MWh of heating and 13,500 MWh of cooling are used in 2015. The manufacturing companies vary from metal processing to fast moving consumer goods. Hourly demands and wind speed, steam production, and solar shining strength are used as input data to the model. Natural gas turbine is used to support renewable systems in addition to the grid. The costs of energy generation by natural gas or wind turbines are taken as unit cost TL/kWh. Storage is also considered in our case, because of high variation in wind speeds. For sales price of electricity day ahead prices are taken and three different pricing in 24 hours are taken into account. Average energy generation cost is almost three times the maintenance cost.

Assumptions of the system include:

a) Maximum 30 MW can be purchased from the grid in an hour;
b) Natural gas turbine for 40 MWh is used;
c) Natural gas boiler has a capacity of 5 MWh for heating;
d) Storage capacity is limited to 20 MW;
e) Demand, wind speed and solar strength are limited to average amounts for the MIP problem.

Algorithms are programmed using C# and run in GUROBI solver for achieving the solutions.

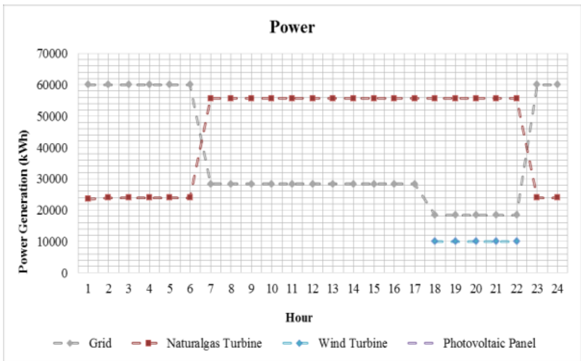

Fig. 3. Electricity generation schedule using the MIP model.

As seen in Fig. 3, the for the minimum cost obtained, electricity generation uses the grid, the natural gas turbine and the wind turbine mainly in the evenings; a fixed heating at 25000 kWh uses only the steam created by the natural gas boiler, and, cooling fixed at 1500 kWh uses only electricity.

Stochastic model considers seasonal changes of wind strength and solar shining for winter, spring, summer and fall as well as making a schedule using the day ahead pricing and 3 days in a raw. Meteorological data is used for uncertainties based on the nature.

The three days

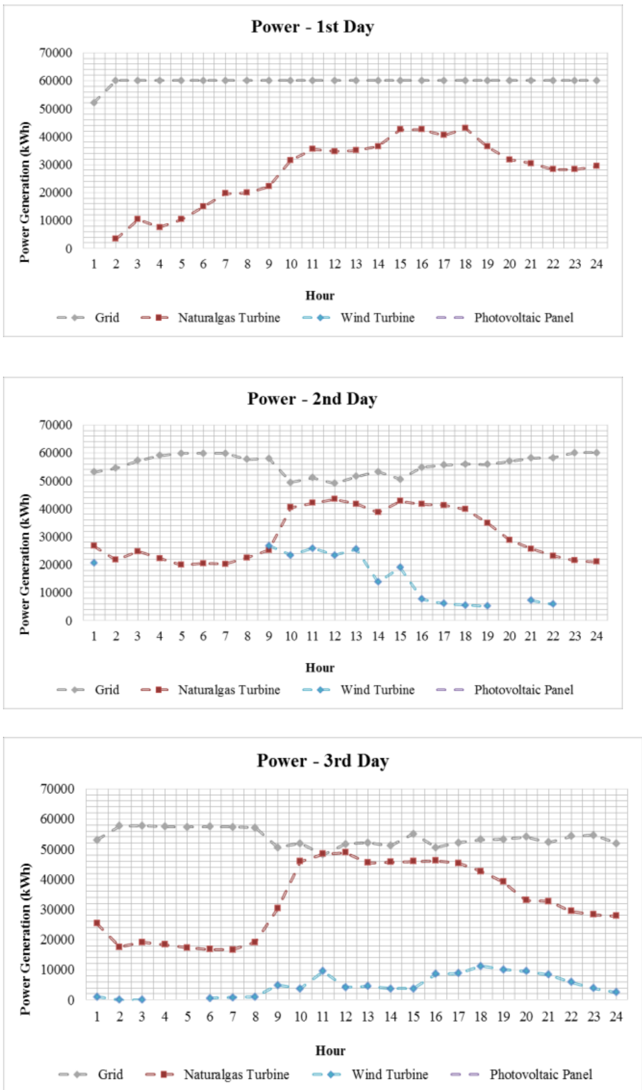

Figure 4. Electricity Generation Schedule for three days using the Stochastic Model.

With the lowest cost achieved using the stochastic model, no wind turbine use in the first day schedule. Almost 10 hours of wind energy are used in the second day and on the third day wind energy is used for 22 hours. However no solar energy is used for three days. In heating and cooling no renewable energy use is observed for three days. The steam is used for the second day of heating but only electricity and heating are used for responding the cooling demands.

Stochastic model shows a wider differentiation considering the seasonal effects and meteorological data changes. It shows corrections according to price and demand changes as well as wind speed and solar effect differentiations.

For the case studied a small wind turbine can be useful but there is no need for the photovoltaic investments.

VI. Conclusions

A hybrid renewable trigeneration system model, comprising wind turbine, photovoltaic panels, thermal collectors, natural gas turbine and natural gas boiler has been developed. Conventional systems that produce only electricity do not seem sufficient to respond the demands of an industrial region because of low efficiency. In an industrial center of manufacturing plants using heating and cooling in processes a tri-generation system is a necessity.

Day ahead or intra day power prices are as uncertain as the demand of a variety of industrial plants working in the same center. It is an unavoidable need to have 24 hours detailed plan to be seen ahead to minimize the energy use. Hence the proposed stochastic model will be helpful in any regional energy usage plans. However, if the costs are considered to be more important than the environmental pollution created the natural gas turbines and natural gas boilers seem to be enough to support the national grid usage. If climate change awareness is developed in these regions, the objective will be more ecologically concerned and then gives the opportunity for the renewable energy use for the regional grid.

The proposed system will be developed to consider the mitigation and adaptation concerns of an industrial center

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