# District Energy Systems: Theory and Applications

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**ABSTRACT**

This paper is about the mutual relationship between a sustainable society and district energy systems. Basics of district energy systems are discussed in terms of energy and exergy efficiency, better utilization of alternative and waste energy resources, and carbon emissions mitigation. A concept city application is briefly explained and evaluated.

**Keywords:** District Energy, Exergy Efficiency, Carbon Emissions, District Cooling, Combined Heat and Power

# Bölge Enerji Sistemleri: Kuram ve Uygulamalar

**ÖZET**

Bu makalede sürdürülebilir bir toplum ile bölge enerji sistemleri arasındaki karşılıklı etkileşim konu edilmektedir. Bölge enerji sistemlerinin temelleri enerji ve ekserji verimliliği, atık ve alternatif enerji kaynaklarının daha akılcı değerlendirilmeleri ve $CO_2$ salımlarının azaltılması boyutlarında incelenmektedir. Bu bağlamda, kuramsal bir kent uygulaması özetlenmekte ve değerlendirilmektedir.

**Anahtar Kelimeler:** Bölge Enerji Sistemi, Ekserji Verimi, Karbon Salımları, Bölgesel Soğutma, Birleşik Isı ve Güç

## 1. INTRODUCTION (GİRİŞ)

Any society faces four conflicting parameters namely, environment, energy, human welfare, and economy in the quest of sustainability. The ideal solution depends on how successfully these four conflicting parameters are resolved without compromise. In the built environment, the best proving ground of this kind of resolution and technology development arena is the district energy system. Implementation of large-scale, long-term, and sustainable energy and exergy efficient conversion, distribution, and utilization systems start with and ends with distributed and district energy and power systems. With growing concerns about human-responsible global warming emissions, green building and high-performance building concepts, nations and communities are focusing rapidly on green communities, districts, and cities. In this quest, DE systems play an important role due to their several advantages, including but not limited to; energy efficiency, heat island effect mitigation, cost efficiency, carbon emissions reduction [1]. DE systems are not new -more than a century old- but what is new is a completely different mind-set of diverse balancing of natural resources with human needs in a mutually sustainable manner. For example, the concept-city of New Mexico envisions simultaneous use of wind, hydro, geothermal, bio-fuel, and solar energy along with locally rich fossil fuel reserves in such a blend that the net outcome is a highly sustainable and environment friendly built environment [2]. In this concept one of the major contributors is a green electric power grid and district energy systems. Especially in sun-belt regions all over the world, district cooling (DC) market is in fact booming [3]. For example, over the past ten years DC saw a rapid growth in the Gulf States. Now has a capacity of just over 6300 MW.

Considering that district cooling technology may be 40% more efficient than conventional air-conditioning, current capacity in the Gulf States is expected to reach 22800 MW by the year 2015. For this growing trend, district heating and cooling system for the 10.2-hectare Tokyo Sky Tree Area is another typical example. This system, which satisfies heating, cooling and service water loads, utilizes geothermal energy and is expected to curb annual carbon emissions by 43% to 48% compared to distributed-cooling systems [4]. DE system is not only a bridge between the energy conversion plant(s) and the end-using buildings. First, in order to facilitate the benefits of DE, resource exergy and demand exergy must be well balanced, which makes it necessary to use low-exergy buildings [5, 6, 7] and low-exergy comfort cooling terminals, like chilled beams [8], and radiant panels [9]. Second and even more importantly, like the name already implies, a DE system should also involve high-efficiency energy conversion and power generation chain of the entire system. This puts under the radar screen the option of cogeneration and poly-generation systems [10]. In this study, an earlier geothermal-lignite fluidized bed concept design [11] was re-visited for the city of Aydın and an upgraded version of the original design [12] was further refined and improved. The region is rich in geothermal, solar, hydro, and lignite.

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## 2. THEORY (KURAM)

According to the Rational Exergy Management Model (REMM) any human activity related to energy involves three tiers of carbon emissions [13, 14]:

$$\sum CO_{2i} = \left[\left(\frac{c_i}{\eta_i}\right)+\left(\frac{c_j}{\eta_i\eta_T}\right)(1-\psi_{Ri})\right]\times P_h+\left(\frac{c_j}{\eta_j\eta_T}\right)\times P_e \qquad (1)$$

In Equation 1, the first terms relates to carbon emissions from energy conversion systems using primary energy resources to generate useful energy-mostly heat. The third term relates to power generation systems-mostly electric. The second, yet the most important term relates to avoidable carbon emissions due to exergy inefficiencies in all energy and power related activities. This term remained hidden so far and concealed the real benefits of district energy and power systems.

district. The plant is responsible to supply all of them in such a manner that carbon emissions need to be minimized. Furthermore waste heat and alternative energy resources must be utilized in order to substitute fossil fuels within the local limitations and availability of alternative energy resources. For example, geothermal, solar, wind, small hydro, biomass and others may not be readily available in sufficient amounts. This condition necessitate to blend them in a hybrid format to cumulate partial alternative energy resources and combine them together according to local conditions and let them provide energy and power in a near-continuous regime. For example solar and wind energy resources have about seven hours of peak-power period difference. This makes it possible to stretch out their base supply rates for a longer period of the day. Obviously in many cases alternative and waste energy resources will not be sufficient to satisfy the entire

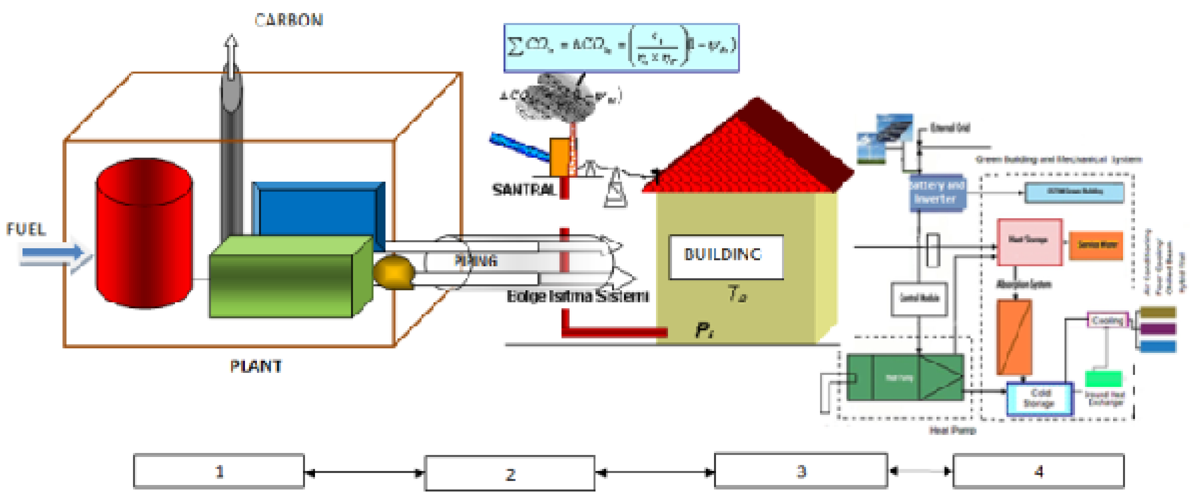


Figure 1. Four Stages of District Energy and Power

In a successful DE system there are four, yet to be well balanced and carefully interrelated stages, which are shown in Figure 1. These stages need to be carefully designed in an integrated format, balanced, and interfaced for minimum energy loss, minimum carbon emissions, and maximum exergy efficiency. These stages are:

1- Plant,
2- District piping,
3- Buildings,
4- Mechanical and electrical system in buildings.

A typical DE system is primarily expected to satisfy the thermal loads (like steam use, comfort heating and cooling, process heat), power, and service water (hot and regular) loads and requirements in the demand and fossil fuels remain a supply option. In this case however, it is almost an absolute necessity to employ co-generation or poly-generation systems in order to maximize the energy and exergy efficiency. In a typical central co-generation plant the energy efficiency is about 90% in heating and the exergy efficiency is about 60%. Compare the latter with a condensing boiler used for space heating. In this case the exergy efficiency is only about 6%. A ground-source-heat pump running on grid power has only about 12% exergy efficiency. Therefore it is very critical to see how exergy efficiently the primary energy resources are used in the plant for minimum carbon emissions (See Equation 1). An ideal DE plant should compromise several energy conversion systems and energy resources carefully bundled in an environmentally conscious manner. Such a plant is shown in Figure 2

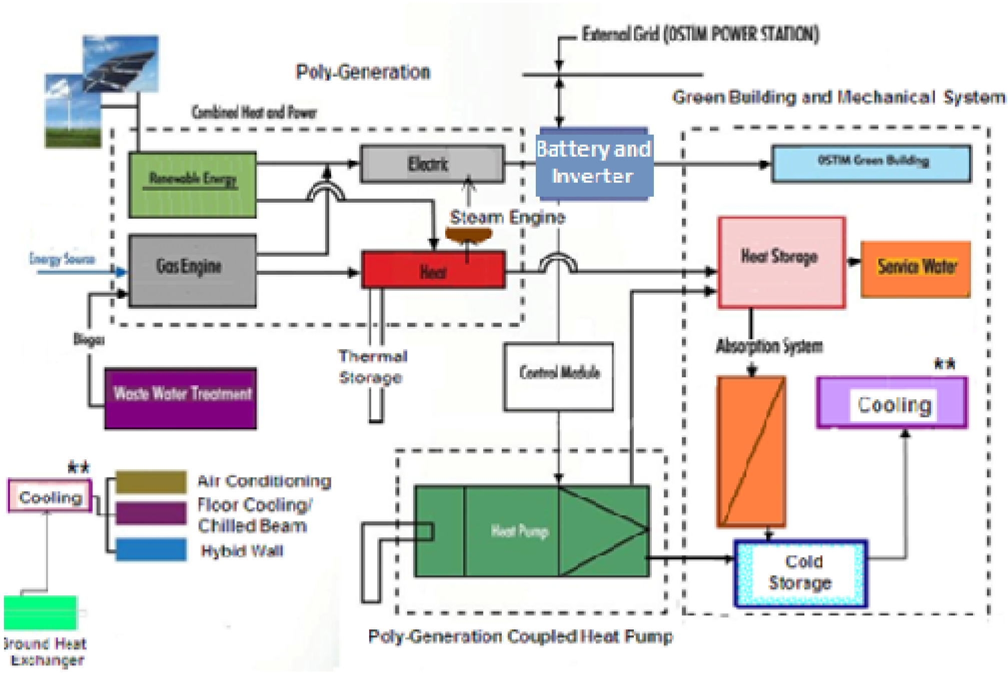


Figure 2. Closed-Loop, High Energy and Exergy Efficiency District Energy Plant

The second important stage is the energy and power distribution system in the district. Generally the installation cost of the plant decreases with the overall capacity, but the piping and other energy transfer costs and operating cost of the distribution cost increase. Therefore, satellite plants seem to be more reasonable and feasible in many cases.

The third stage is the energy and power demand points in the district like buildings. Several applications need to be enthalpy and temperature cascaded such that waste of one application becomes the energy input of the other. Low-exergy buildings, energy conservation methods and use of on-site alternative energy resources at this stage further help to approach the ideal DE solution.

Finally the mechanical and thermal systems at the points of demand need to be optimized and made compatible with DE supply characteristics. Another important aspect is the energy storage systems, which are essential to shave-off the peak loads and let the systems run continuously at base loads with their peak efficiency.

## 3. CONCEPT APPLICATION FOR THE CITY OF AYDIN (AYDIN KENTİ İÇİN KURAMSAL UYGULAMA)

Aydın is located in the Western Anatolia in the hinterland of the Aegean Region. The region has rich geothermal and lignite reserves. Small hydro-power, solar, and wind energy potential are also available. Currently, lignite is not efficiently utilized and has high carbon emissions rate. Yet lignite is an important energy, employment, and economical potential in that area and may not be ignored in the development of regional energy and environment strategies. Therefore, in this study lignite has been categorized as a clean energy resource by developing a hybrid, fluidized-bed, hydrogen-producing energy source coupled to geothermal reservoirs in the city. The overall heat output is categorized as "Waste Heat." The problem of optimum district energy system was solved at three levels, namely; energy resource, energy conversion and power production, and finally district energy system. Local availability of lignite was taken to be an important asset and factored-in to the optimum solution by making this fossil fuel greener by employing fluidized-bed technology.

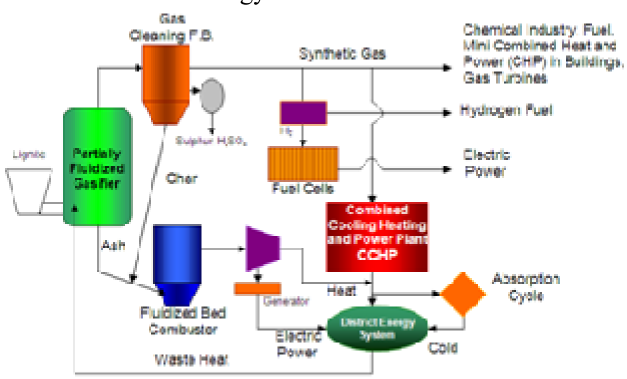


Figure 3. Central plant for clean hybrid lignite utilization system.

Due to the fact that both lignite reserves and geothermal energy resources are abundant in the area, and very important for a longer-term employment, economy, and economic stimulus, lignite and geothermal energy, together with the waste heat of them were selected for the primary energy supply system.

The second geothermal central plant cascade supplies heat and power to the same satellite DE plants.

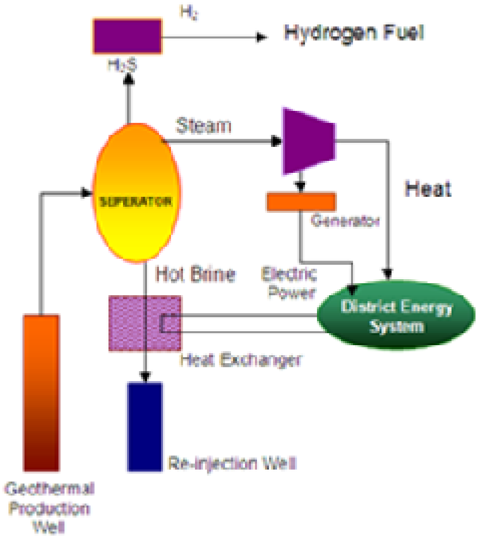


Figure 4. Central geothermal plant layout.

Central hybrid-lignite plant and the central geothermal plant are functionally synchronized and coupled for the DE system. This coupling is shown in Figure 5. The district energy system is optimized for the number of satellite DE plants by Equation 2 [10]. The first term in Equation 2 represents the optimum DE circuit length for feasible cost and the second term represents the proportionality between the pipe size and pipe cost for fixed Reynolds number for different district capacities, $P$ (MW).

$$\sum L\max = N \times \left[ a + \left( \frac{P}{N} \right)^{0.9} \right] + \frac{P}{N} \qquad (2)$$

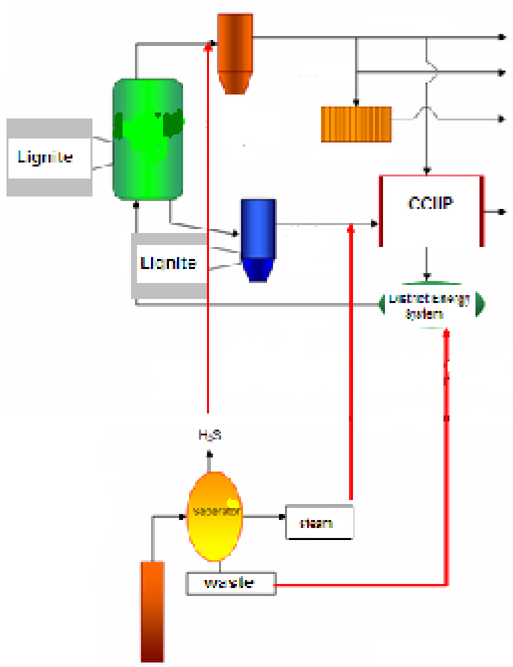


Figure 5. Hybrid clean lignite and geothermal plant coupling for Aydın DE system.

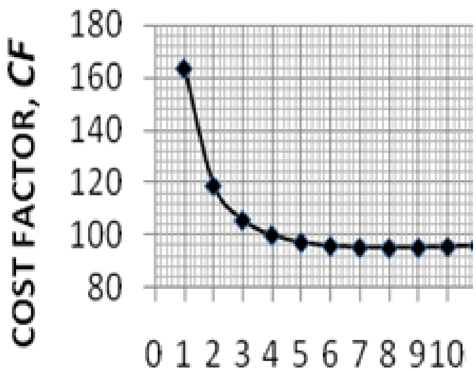


Figure 6. Determination of the optimum number of DE satellites.

For a total of 100 MW thermal capacity Equation 2 gave the optimum number of satellite DE plants to be eight (See Figure 6). Here, the cost factor, $CF$ is associated with Equation 2. According to Figures 6 7, eight satellite plants are almost evenly distributed within the city. The central hybrid lignite-geothermal plant is located near the industrial park, which also represents a demand point for the DE system. Main DE lines feed the satellite plants and each satellite plant feed their own district that each have approximately 12.5 MW thermal load. Because the heating and cooling piping have different flow regimes, power, cold, heat, DHW services are serviced through below-the-ground conduits

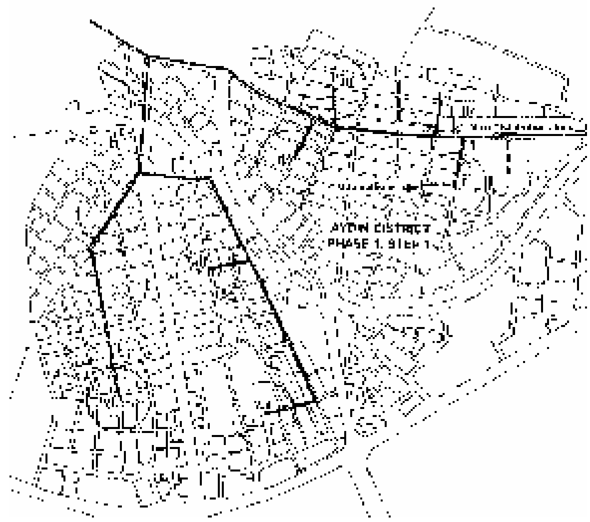

Figure 7. Optimum district cooling and heating system for Aydın.

In summer the temperature drop across the cooling circuit is 10°C maximum, compared to 20°C for heating in winter. Therefore, although the cooling penetration in Aydın is less than heating, the district piping for cooling must have almost the same size of heating pipes in order to reduce pumping costs. The district circulation pumps are speed, load, and exergy-balance controlled. Supply temperatures for both heating and cooling seasons are controlled for maximum $\Psi_{Ri}$ and minimum kinetic exergy of the moving fluid.

## 4. DISCUSSION (TARTIŞMA)

The building sector represents 40% of total energy consumption in the European Union [15]. Energy consumption in this sector would, therefore, substantially undermine the global efforts to reduce harmful gas emissions. For this reason the European parliament and European Commission released Directive 2009/91/ES on the energy performance of buildings [15]. In all these efforts a very important aspect of energy resource utilization is ignored, which is the rational exergy balance between demand and supply points of energy. In fact conventional heating and cooling systems annually utilize only about 5% of the resource exergy on average [16]. This is a strong indicator that exergy must be better managed in the quest of carbon emissions reduction to at least decelerate global warming due to human activities. District energy systems offer substantial energy savings and reduction in harmful gas emissions, especially because they can accommodate exergy-efficient combination of fossil and alternative energy resources in a nested, cascaded hybrid form and may easily incorporate new energy conversion technologies like co-generation. This study has shown that decision making process must incorporate the concept of exergy in all aspects of DE system design, analysis, and evaluation. By using REMM for the city of Aydın, a hybrid DE system with optimal number of DE satellite plants and with incorporation of local fossil fuel reserves and geothermal energy has just accomplished what the EU Directive sought for: sustainable, competitive, and secure energy. Environmentally clean and exergy attributes were also added to the EU vision in the city of Aydın. Carbon emissions are predicted to decrease by 94% when compared to split-type air conditioners. In winter a similar reduction is possible.

This study has demonstrated that a careful blend of fossil fuels with alternative energy resources and their derivatives like hydrogen, clean and proven technologies like fluidized-bed combustion offer hybrid solutions for optimum solutions. The key to success is to carefully take into consideration the constraints and benefits of local resources, energy and power demands, and optimally balance the four stages of district energy systems.

## 5. SYMBOLS (SİMGELER)

| | |
|---|---|
| $a$ | Constant distance in Equation 2, km |
| $CF$ | Cost factor, dimensionless |
| $c_i$, $c_j$ | Combustion carbon equivalency of the fuel used in the building and the power plant, kg $CO_2$/kWh |
| $CO_{2i}$ | Direct and secondary carbon emissions (or rate), kg $CO_2$ (or $CO_2$/day) |
| $L_{max}$ | Maximum allowable distance between the energy supply and the district, km |
| $N$ | Number of satellite DE plants, dimensionless |
| $P$ | Power transmitted in a district circuit, MW |
| $H$ | First-law efficiency, dimensionless |
| $\Psi_R$ | Rational exergy management efficiency, dimensionless |
| $\Sigma CO_{2i}$ | Compound carbon emissions (or rate), kg $CO_2$ (or kg $CO_2$/day) |
| □$CO_2$ | Avoidable carbon emissions (or rate), kg $CO_2$ (or kg $CO_2$/day) |
| DC | District cooling |
| DE | District energy |
| DHW | Domestic hot water |
| REMM | Rational Exergy Management Model |

Subscripts

| | |
|---|---|
| $\dot{I}$ | Building |
| $J$ | Plant |
| $T$ | Transmission |

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