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Trends in the Studies of Heat Island Mitigation Technology — Analysis from the Viewpoint of Energy Use —

MASAHIRO NEMOTO AND HIROKAZU KOBAYASHI *(Visiting Researcher)*
Environment and Energy Research Unit

5.1 Energy use and urban problems

Careful considerations of urban economic development and environmental issues arouse concerns that extreme urbanization may hamper the growth of a city and deteriorate the environment. The heat "island effect" is a phenomenon where aboveground temperatures in a city become higher than those in its suburb. A situation in which all the city dwellers depend on air conditioners to sleep on sultry nights is undesirable for the urban environment. In addition, it is pointed out that the concentration of air pollutants above the city and considered localized torrential rainfall are partly due to the heat island phenomenon[1] .

The pattern of energy use (electricity, oil, gas, etc.) in Japan indicates that a large part of energy is being consumed in the city. Consumed or used energy is eventually converted to heat, most of which is released into the air. In this sense, the heat island phenomenon can be considered as a typical example of environmental issues related to energy use – i.e., the introduction of energy into the city and its consumption. It is thus very important to discuss the heat island effect from the viewpoint of energy.

Chapter 5.2 of this article provides an overview of the heat island effect; Chapter 5.3 introduces mitigation measures such as the interception and discharge of heat energy; Chapter 5.4 addresses the impact assessment of urban waste heat associated with the introduction of cogeneration systems; and Chapter 5.5 provides a summary of the heat island phenomenon from the viewpoint of energy use, while suggesting another viewpoint that is needed for studying heat island mitigation measures in the future.

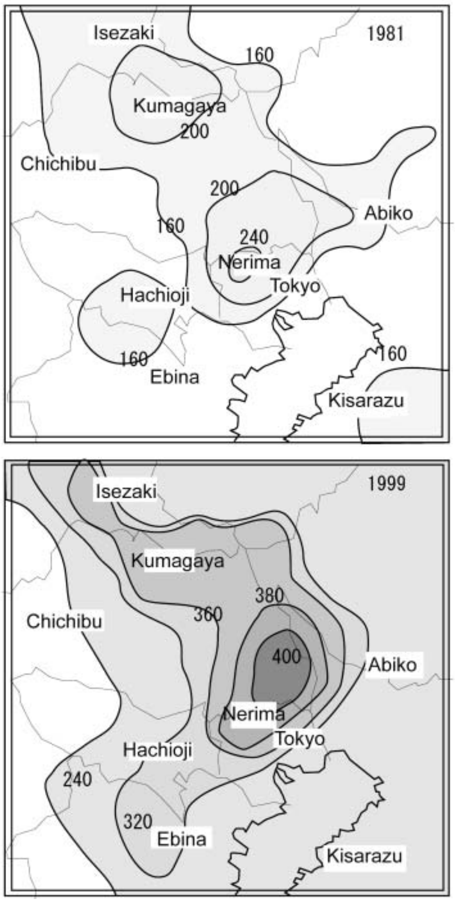
5.2 The present state of the heat island

5.2.1 *The present state of the heat island phenomenon*

The heat island was considered to be a phenomenon limited to large cities like Tokyo and Osaka. This problem, however, is now emerging in local cities such as Fukushima (population: 290,000), Shizuoka (470,000), Hikone (110,000) and Kumamoto (660,000) [2]. Specifically, periods with temperatures above 30 °C are becoming longer and sultry nights are on the rise in all of these cities. Higher temperatures in the summer months boost demand for air conditioning, thereby increasing power consumption. And higher operating rates of thermal plants to meet the increasing power demand will lead to additional CO_2 emissions. For this reason, the heat island effect is by no means a localized problem attributable to the activities of each citizen. Rather, it is a global problem.

The distribution of temperatures in large cities like Tokyo and Osaka can be represented in a contour form, the center of which exhibits the highest temperature. The term "heat island" derives from the shape of this contour form, which looks like the map of an island. Various observations indicate that the recent unusually hot summers in large cities are not due to climate changes associated with global warming. For instance, the annual average temperature in Tokyo has increased by some 2 °C in the last century — a level that far exceeds that of global warming [2]. Figure 1 shows the distribution of the total number of hours with

Figure 1: Areas with higher temperatures in the Tokyo Metropolitan area (1981 and 1999)[3]



(The distribution of the total number of hours with temperatures above 30°C per year.)

temperatures above 30 °C; areas with higher temperatures have expanded dramatically over the last two decades.

The major causes of the heat island are: the increasing use of energy, which results in an increase of waste heat discharged into the atmosphere; the amount of evaporation (transpiration) from plants, which is decreasing due to shrinking green space – i.e., a decrease in the amount of energy converted from sensible heat to latent heat (see Footnote 1); and the thermal storage by increasing concrete buildings and asphalt pavement.

Footnote 1: Sensible heat and latent heat

Water absorbs heat from the surroundings when it evaporates. In other words, it needs heat to convert itself to water vapor. In this sense, water vapor can be regarded as a special form of energy called "latent heat." A general form of energy, meanwhile, is referred to as "sensible heat."

5.2.2 Modeling of the heat island

In order to solve the problem of the heat island, there is a need to model the phenomenon itself and evaluate the effectiveness of possible measures against it. A number of organizations and research institutes here and abroad are modeling the heat island. This section addresses a model developed by the Tokyo Metropolitan Government as a representative example.

The Tokyo Metropolitan Research Institute for Environmental Protection developed a forecasting model of mitigation measures to address the heat island. The model covers an area including Tokyo Metropolis and eight prefectures surrounding it, the radius of which is several hundred kilometers; the vertical distribution of temperatures, the direction/speed of wind, and humidity can be forecasted by this model.

The amount of artificial waste heat in the area, a factor indispensable for the calculation, is estimated based on the energy consumed by factories/businesses, residences and automobiles. Specifically, the amount of waste heat in Tokyo Metropolitan is estimated at 165 Pcal per year, about 70% of which originates in the 23 wards of Tokyo. The breakdown by source is as follows: factories/businesses, 46%; automobiles, 27%; and residences, 27%. The artificial waste-heat intensity in the 23 wards stands at some 185 Mcal/m^2 per year – more than four times the amount estimated in the cities in Tokyo, or almost one fifth of the annual amount of solar radiation in the Tokyo area, which is 990 Mcal/m^2. In particular, the intensity in the three wards located at the center of Tokyo is estimated at 358 Mcal/m^2, about one third of the total.

The forecast model is based on the following four cases:

— Case 1: Energy consumption will be reduced by some 6% through long-term, effective measures.

— Case 2: The area of parks will be doubled, while 7% of the area for buildings will be converted into green space.

— Case 3: Of the total road area, 10-20% will be paved with permeable materials.

— Case 4: Case 1, 2 and 3 (permeable

pavement: 20%) will all be put into practice.

Based on the observational data on summer days (August 31 to September 1, 1992), the climatic data that were available (temperatures, wind direction, wind speed, etc.), the effects of mitigation measures against the heat island phenomenon were forecasted for each of the four cases mentioned above. The following are the results:

a. A 6% reduction in artificial waste heat has virtually no impact on the maximum daily temperature. The minimum daily temperature, however, is reduced by 0.05 °C at the center of Tokyo.
b. Of all the mitigation measures, the promotion of urban greening is most effective in reducing the maximum daily temperature; a maximum of 0.37 °C is reduced in the northwest part of the area comprised of the 23 wards, most likely due to increased transpiration by plants. The minimum daily temperature is also reduced by 0.14 °C.
c. With 10% of the total road area paved with permeable materials, the maximum daily temperature is reduced by 0.02 °C; and with 20%, by 0.05 °C at the center of the city (less effective compared with the promotion of greening).
d. With the above three measures implemented together, the average daily temperature is reduced by 0.23 °C in the northwest part of the area comprised of the 23 wards; the maximum daily temperature, by 0.43 °C; and the minimum daily temperature, by 0.15 °C at the center of the city.

The modeling of the heat island phenomenon in the report prepared by the Ministry of the Environment shows similar results [3].

5.3 Trends in heat island mitigation technology

As already mentioned in Chapter 5.2, the promotion of urban greening contributes dramatically to mitigating the heat island phenomenon. It should be noted, however, that there is an essential difference between expanding urban green space (the trees and plants in parks, roadside trees, etc.) and promoting urban greening where flowering plants, etc., are planted in order to offer visual comfort to the citizens. In places like Japan, where land prices are very high, creating a sufficient area of green space in the city is by no means easy. And it is not feasible to dramatically reduce artificial waste heat in a short period of time.

Feasible measures for mitigating the heat island phenomenon inevitably involve the improvement of buildings, land use, and economic activities in the city.

5.3.1 Trends in the technology for shielding buildings from heat (as part of architectural engineering)

The heat island phenomenon is partly due to an increase in the temperature of external building surfaces because of solar radiation. Effective measures such as reflecting solar radiation or shielding the interior of buildings from heat are being studied.

(1) Heat reflective construction

Heat-shield coating is applied to roofs, rooftops and other parts of a building exposed to solar radiation in order to reduce the surface temperatures. Special types of coatings and coating techniques are available — e.g., a coating containing ceramic balloons (small hollow particles made of ceramic), which reflects infrared radiation, and a two-layer coating technique with the lower layer made up of a low-thermal-conductivity coating, and the upper layer of materials that reflect visible light and near infrared light of insolation.

(2) Heat insulation by rooftop greening and vegetation medium

This measure involves vegetation and its planting media on the rooftop, both of which shield the building from heat. Rooftop greening is becoming widespread in the city because of its contribution of improving visual amenity. The Tokyo Metropolitan Government, for instance, enforced the Nature Conservation Law in order to plant 20% of the total area of rooftops with vegetation.

From April 2001, moreover, an incentive system was put into place — i.e., greater floor area ratios are granted to those buildings promoting rooftop greening.

Vegetation evaporates water it absorbs from the ground, thereby cooling down the temperatures of leaves and their surroundings; it eventually prevents the temperature of the ground surface from rising by converting sensible heat of solar radiation to latent heat (see Footnote 2). By contrast, rooftop greening using plants resistant to hot and dry weather cannot lower the temperature inside the building proactively, though it shields the building from heat to some extent.

Since rooftop greening involves an increase in the live load on the building, special techniques are required for its introduction — e.g., planting of succulent plants such as Sedums (see Footnote 3). Sedums can grow on a thin planting medium that contributes to reducing both the live load and the maintenance cost. By using polypropylene and ceramic soil as materials, the thickness of a planting medium can be reduced to 50-60 mm, and its weight, to less than 40 kg/m^2, both of which are less than one third of those of a typical planting medium for turfs [5].

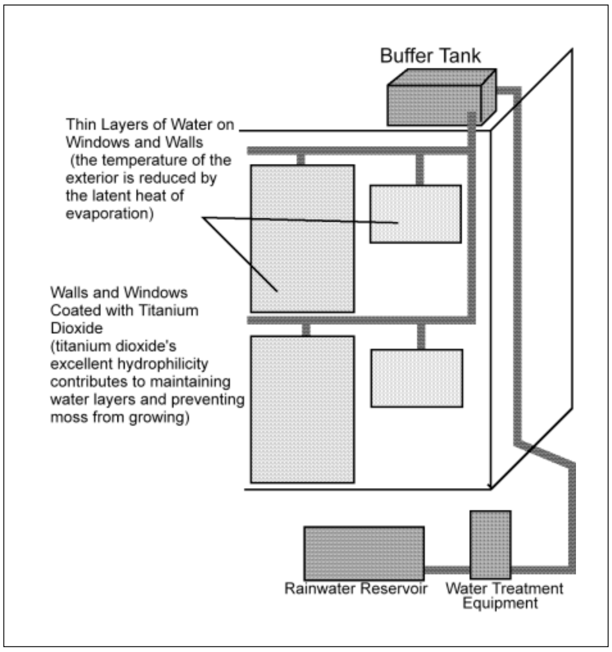
Footnote 2:

The surface temperature of vegetation that is sufficiently watered will not rise over 32 °C, according to some studies [3].

Footnote 3:

A generic name for small, fleshy CAM (Crassulacean Acid Metabolism) plants — herbaceous perennials belonging to Crassulaceae (sedum family). CAM plants open the pores to absorb CO_2 during the nighttime and convert it into malic acid. During the daytime, they close the pores to prevent the loss of water through transpiration, while reconverting malic acid into CO_2 for photosynthesis. CAM plants are very robust and resistant to environmental stresses such as hot, cold and dry weather; they can grow on infertile, thin-layer soil and require no particular maintenance.

Figure 2: Concept of exterior surface cooling system using photocatalysts [6]



(1) Cooling of surface temperatures through engineered evaporation systems

A thin layer of water on the exterior surface of rooftops and walls reduces the temperatures of the building and its surroundings — the effect of latent heat due to the evaporation of water. Materials coated with photo catalysts form a very thin layer of water on their surface. By taking advantage of this property, the amount of water necessary for keeping the surface of rooftops and walls wet can be reduced dramatically. In the case of a 10-story building, for instance, one-third to one-sixth the annual rainfall on the site of the building would be sufficient to keep its rooftop and walls wet for one month in summer (Figure 2).

Photocatalysts also add antifouling and anti-algae properties to wall materials, thereby reducing the maintenance cost of the building. A prefabricate cottage was previously set up using materials coated with titanium dioxide, a typical photocatalyst; a thin layer of water was formed on its exterior surface. The results: the temperature of its interior was about 10 °C lower than that of the interior of an ordinary cottage [6].

(2) Proactive use of fresh air for high-rises

Because of the widespread use of IT equipment in an office, some high-rise office buildings need to be air-conditioned even during the winter months. In a bid to reduce the amount of energy consumed by mechanical air-conditioning, therefore, the construction of a new-type of high-rise is under study; its concept is to introduce cool, fresh air directly into the office. Unlike low-rises, the windows of which can be opened and closed, introducing fresh air into the interior of high-rises requires new techniques. Several methods have been developed in order to address this problem — e.g., a control system responding to exterior climatic conditions (temperatures, humidity, etc.), a design of air ducts in consideration of equipment layout plans of the office, and a simulator for controlling the heat environment [7].

5.3.2 Trends in the studies of ` cooling technology (as part of urban environment engineering)

(1) Studies of new paving materials

Since most of the road in the city is paved with non-permeable materials such as asphalt, water does not evaporate through the pavement — a clear contrast to land covered with vegetation. Thus, cooling by the consumption of latent heat rarely takes place in the city. In addition to this, several problems associated with non-permeable pavement have been pointed out from the viewpoint of hydrology — e.g., rainwater in the city immediately flows into sewage-treatment plants. In order to address these problems, there have been some attempts to commercialize permeable pavement. Their basic idea, however, was to make the pavement permeable by means of fine pores, most of which clog over time; although permeable, non-water-retentive paving materials did not create much of an evaporative cooling effect.

Other R&D are underway, the common idea of which is to impregnate paving materials with chemical absorbents or dehumidifying agents (chlorides), thereby providing the materials with water retentivity and the properties of absorbing and releasing moisture. Cost reduction efforts are also underway by using seawater as a material for producing chlorides [8].

There are some examples where the performance of paving materials having both permeability and water retentivity was tested in the field [9]. Specifically, powdered blast furnace slag (a byproduct of the iron-making process) was used as a water-retentive material, which was then filled in part of the openings of the drainage asphalt pavement to provide it with both of the properties.

(2) Studies for using groundwater as a heat sink

Conventional air-conditioners release heat into the atmosphere through their heat exchangers. New technologies are being developed for transferring exhaust heat to groundwater through heat pipes buried underground. This method is expected to contribute to mitigating the heat island phenomenon, since it does not involve any release of heat into the atmosphere [10].

(3) Studies for selecting plants with high transpiration capacity

Plants absorb water through their roots and the absorbed water evaporates from the leaves. This transpiration capacity of plants (evapo-transpiration) can be compared to a powerful, low-cost "pump" that removes water from the soil. There are some plans for taking advantage of this particular capacity — e.g., using plants to absorb both water and toxic substances from polluted soil, or in the case of arid countries, planting vegetation all over the soil of waste dumping areas to pump rainwater into the atmosphere, while preventing it from permeating through the waste layers [11].

This "pumping effect" of plants can be used to cool down the atmosphere. In other words, it is possible to mitigate the heat island phenomenon by activating the transpiration capacity of vegetation, which in turn requires the selection and introduction of optimal vegetation. Informative studies are underway in the U.S. and other countries for selecting plants with high transpiration capacity, the purpose of which is to materialize the phytoremediation of polluted soil [12].

5.4 Evaluation of the impact of energy supply systems

A variety of mitigation technologies mentioned in the previous chapter are expected to mitigate the heat island phenomenon without interfering with the current economic activities. Meanwhile, decentralized power sources such as fuel cells and gas turbines — cogeneration systems with higher energy efficiency — will probably become widespread in the city. Accordingly, small-scale energy supply systems designed for specific buildings or districts are expected to emerge in the near future.

5.4.1 Ideal energy supply systems and their waste heat

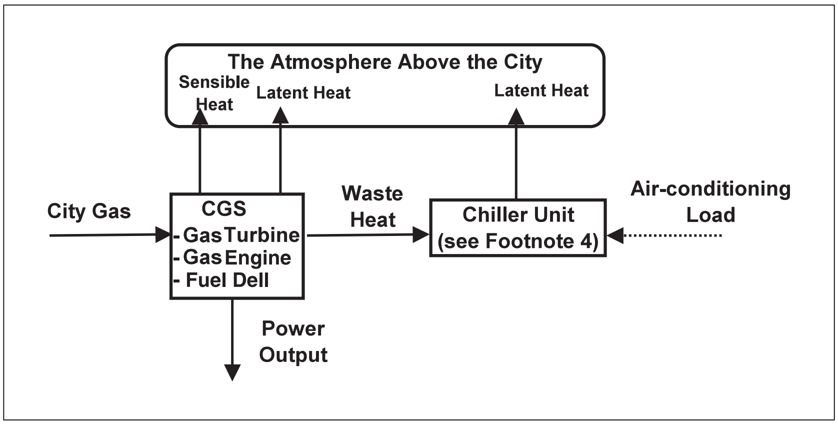
Electric equipment including the air-conditioners of buildings in large cities depends largely on the electricity supplied through electric grids. Power plants, however, are generally located outside urban areas, and their power generation efficiency stands at 40%, more or less. Put differently, about 40% of the potential thermal or nuclear energy is converted into electricity, while the rest is discharged into the sea as waste heat energy.

The power consumption and heat load on the part of energy users, namely offices and residences, fluctuate by day and month, and their patterns do not synchronize with each other [13]. For this reason, distributed power sources are forced to operate in accordance with load fluctuations. In the case of fuels cells and gas turbines (both of which are considered promising distributed power sources), however, lowering of load results in lower power generation efficiency [14-16]. Taking fuel cells as an example, the power generation efficiency at 100% load factor stands at some 40%, while it decreases to some 36% at 25% load factor (some data show that in the case of 1 kW class solid-oxides fuel-cells, the power generation efficiency of direct current output at 1 kW is about 25%, while it decreases to some 15% at 500 W output. [17]) As for gas turbines, the power generation efficiency at 100% load factor is about 32%, which decreases to about 20% at 25% load factor. The heat energy being discharged into the sea will be brought into the city together with distributed power sources. Moreover, their lower power generation efficiency means that a massive amount of waste heat will be generated — a situation that will further accelerate the heat island phenomenon.

5.4.2 Evaluation of the amount of waste heat generated by energy supply systems

A group of Dr. Yutaka Genchi of National Institute of Advanced Industrial Science and Technology (AIST) [18] and another group led by Assistant Professor Yoshiyuki Shimoda at Osaka University [19] are currently conducting studies on the ideal energy supply system and its relation to the heat

Figure 3: Concept of energy flow incorporating a cogeneration system [18]



Footnote 4:

A chiller unit is a cooling device that uses water or air as a refrigerant. The refrigerant in the primary circulation absorbs the heat generated by mechanical equipment; the heat absorbed is then transferred to the refrigerant in the second circulation, which is eventually dissipated either through evaporation or air cooling.

island phenomenon.

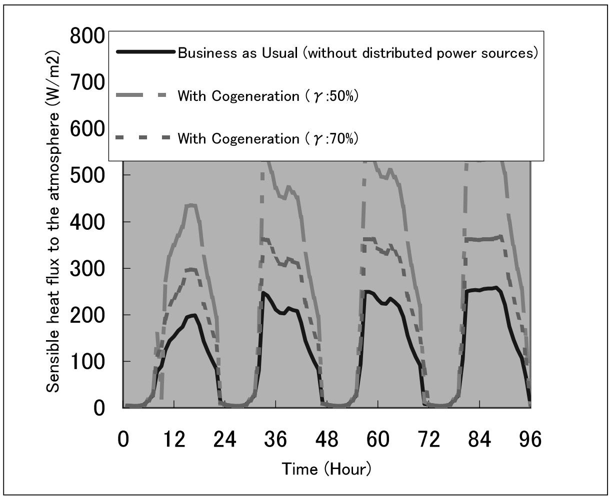
Based on an energy flow that incorporates a cogeneration system (CGS) (see Figure 3), Genchi's group simulated the amount of heat discharged into the atmosphere above the Dojima district of Osaka City as well as changes in temperatures. This simulation used the weather observation data for the period between July 29 and August 2, 2001.

Figure 4 shows hourly fluctuations in the sensible heat flux to the atmosphere. It compares the case without distributed power sources to that based on CGS with varying combined efficiency (γ: power generation efficiency + heat efficiency). At 70% combined efficiency, the amount of sensible heat discharged is almost consistent regardless of the introduction of distributed power sources, whereas at 50% combined efficiency their introduction results in more than twice the amount of sensible heat discharged under the case without distributed power sources; an increase in the temperature is estimated at 0.7 °C.

Shimoda's group, meanwhile, is conducting research on how the energy use in each sector of consumer, industry and transportation would influence the temperature in Osaka. Specifically, the group quantified the amount of each energy source (electricity, oil, city gas, etc.) consumed by each sector, and evaluated how the waste heat would be distributed to sensitive heat, latent heat and water systems. In all of Osaka, the total of sensitive heat and latent heat — the annual average of the amount of energy discharged — corresponds to some 10% of the amount of the total solar radiation in the area. Incidentally, the amount of energy discharged is almost equal to the amount of solar radiation in dense city area like Midosuji.

Shimoda's group also conducted a case study of the energy flow in all of Osaka based on the large-scale introduction of regional cogeneration systems. Dividing Osaka into 0.5 km-square areas, the group studied changes in energy flows in the case of introducing CGS (gas turbines using city gas as fuel) into areas, the heat demand density of which is 1 Tcal/ha per year. The power generation efficiency of the gas turbines was assumed to be 30%. Designed to cogenerate heat and power, CGS can operate in response to daily fluctuations in electricity and heat demand. Based on this characteristic, three types of operations were set for CGS: generating all the electricity needed in the area, while supplying part of its heat demand (power-oriented operations); generating all the heat needed in the area, while supplying part of its electricity demand (heat-oriented operations); and generating the electricity without heat excess or supplying heat without electricity excess in the area (no excess capacity). In line with these types of operations, the group evaluated the effect of introducing CGS, compared with the energy supply dependent on thermal plants. According to the results of this case study, the energy-source mix before introducing CGS – heavy oil, kerosene, city gas and grid electricity – will be narrowed down to city gas and grid electricity in all of the operations after the introduction of CGS. Consequently, the total energy consumption is expected to decrease by 10-15%. Regardless of the type of an operation, however, the amount of waste heat in the area will increase since only part of waste heat can be utilized in the region.

Figure 4: Hourly fluctuations in the amount of sensible heat discharged into the urban atmosphere



5.5 Conclusion

The average temperature in July 2002 at the center of Tokyo was 2.5 °C higher than that in a normal year, and temperatures topped 30 °C in 24 days – the record-breaking hot summer of 1994 is becoming a norm. This trend is creating a vicious circle in terms of energy use. Specifically, the worsening heat island phenomenon in the city boosts demand for air-conditioning during the summer, and along with it, the consumption of energy such as electricity, which in turn generates waste heat that would further accelerate the heat island phenomenon.

Mitigation technologies targeting buildings, etc., should thus be developed and promoted, as mentioned in Chapter 5.3. These technologies, however, are all based on the premise that the current production activities and life styles are maintained. In other words, their aim is to pursue measures for maintaining the living standards of a city plagued with the heat island phenomenon. In discussing long-term measures in the future, therefore, there is a need to study the impact of energy use on the mechanism of the heat island.

In the meantime, distributed power sources centered on fuel cells are expected to become widespread in the city and industrial facilities in its suburb in around 2010. As already mentioned, the introduction of the existing distributed power sources, the combined efficiency of which is 40-60% (depending on load conditions), will accelerate the heat island phenomenon. What is needed from the viewpoint of mitigating the heat island phenomenon, therefore, is to develop power sources that can be operated at higher power generation efficiency and heat utilization efficiency within the range of fluctuations in users' demand for heat and power. There is also a need to develop advanced simulation analysis technology to evaluate how the improved distributed power sources and the mitigation measures mentioned in Chapter 5.3 will mitigate the heat island effect. In addition, the development of technology for transferring waste heat generated by distributed power sources to the sea, rivers and ground (media that can absorb a massive amount of heat) holds the key to the success of the efforts.

Discussions about the heat island and measures against it will inevitably wind up in the environment-versus-economy argument. One widely held view is that the only solution to this problem is to review the very concept of the city. For instance, a concept called “compact city” has been proposed — i.e., there should be an optimum scale for each city in view of its living environment including commuting, and, hence, it should be possible to maximize the economic value of the city while minimizing the associated environmental issues at the same time. Although it is by no means feasible to dramatically convert large cities, namely the center of the social system, into compact cities in line with this concept, it may be possible to divide such large cities into compact cities in phases by creating green spaces and promoting energy-efficient buildings when developing urban renewal projects. The creation of a realistic image of a future city, in which a comfortable living environment and efficient energy use go together, holds the key to developing effective measures against the heat island effect.

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