May 21, 2024

A Thermodynamic Consideration of the Aerothermal Energy and Ground Heat Used by Heat Pumps

- The Importance of Heat Pumps and the Interpretation of Aerothermal Energy -

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Summary

Heat pumps are high efficiency equipment that are widely used for air conditioning and water heating and play an important role in the electrification that is promoted toward decarbonization. On the other hand, there need to be careful discussions on the interpretation of the heat that heat pumps use as the heat source, which include aerothermal energy (or ambient heat), ground heat and water heat. In the EU, heat such as aerothermal energy, ground heat and water heat utilized by heat pumps whose purpose is heating and cooling is defined as natural heat, or in other words renewable energy, and a formula to define these types of heat as renewable energy was established for cooling-purpose heat pumps in 2022, followed by a formula for heating-purpose heat pumps in 2009. However, while ground heat and water heat can be regarded as renewable energy in the sense that they utilize differences from the ambient temperature, there needs to be a careful discussion when it comes to aerothermal energy, which has the ambient temperature. This paper, based on a scientific viewpoint, organizes the interpretation of natural heat by comprehensively addressing the mechanism of heat pumps used for heating and cooling.

When the heat (absorbed from the environment) used by heating-purpose heat pumps is aerothermal energy, the aerothermal energy is artificial heat that becomes a usable state only when electricity is input, and since it does not exist originally in nature, it cannot be regarded as natural heat. From this viewpoint, defining the aerothermal energy as renewable energy is inappropriate. It is undoubtedly appropriate to regard the energy obtained by differences between the ambient temperature and the temperature of the utilized heat (such as ground heat and water heat) as renewable energy. When the heat used by heat pumps is ground heat, it can be regarded as renewable energy, as the heat pumps utilize natural heat by exploiting differences from the ambient temperature, but the quantity of ground heat as renewable energy should be defined as the difference in the electricity consumption between an air-source heat pump and a ground-source heat pump, in other words, the amount of electricity consumption that can be saved by elevating the efficiency of a heat pump through utilizing ground heat.

The function of cooling-purpose heat pumps is to remove heat from a certain space and discard the

removed heat to the environment. The EU's Renewable Energy Directive (RED) defines part of this removed heat as renewable energy, but the removal of heat is the provision of cooling and is cooling demand itself; it is not the utilization of natural heat that exploits difference from the ambient temperature. From this viewpoint, it is undoubtedly inappropriate to regard cooling demand as renewable energy. Based on the definition formula in the EU's RED, generating and utilizing more cooling by consuming a larger quantity of electricity will result in more "renewable energy" being utilized. On the other hand, if ground heat is utilized, similarly to the case of heating-purpose heat pumps, the quantity of ground heat as renewable energy can be defined as the difference in the electricity consumption between an air-source heat pump and a ground-source heat pump, in other words the amount of electricity consumption that can be saved by elevating the efficiency of a heat pump through utilizing ground heat.

Even if the aerothermal energy utilized in heating-purpose heat pumps is regarded as "renewable energy" and is added to renewable energies such as solar photovoltaics and wind power to statistically increase the quantity of renewable energy introduced, it is needless to say that the volume of energy consumed and CO_2 emitted by a country or region as a whole does not change. This is because the energy saving effects of the heat pumps that are in operation are already being reflected in a country or region's overall current energy consumption and CO_2 emissions. Consequently, defining the aerothermal energy used by heat pumps as renewable energy and adding it to the quantity of renewable energy introduced ostensibly inflates renewable energy statistics. However, because that aerothermal energy does not have the effects that renewable energies like solar photovoltaic and wind power possess, such as reducing CO_2 emissions and enhancing the self-sufficiency rate, there is a possibility that an intermixed element would be introduced into the original goals of renewable energy policy. Furthermore, in the case of cooling-purpose heat pumps, they do not utilize aerothermal energy, and only supply cooling as a result of electricity consumption by the heat pumps.

Heat pumps are excellent high-efficiency equipment (energy-saving equipment). Increasing the uptake of high-efficiency (as primary energy basis) heat pumps can be expected to have energy consumption and CO_2 emissions reduction impacts. Heat pumps should be promoted on the basis of scientific verification focusing on the intrinsic contributions that renewable energy possesses for reducing CO_2 emissions and enhancing the self-sufficiency rate, rather than focusing on numerical target of renewable energy.

Introduction

Heat pumps are high efficiency equipment that are widely utilized for air conditioning and water heating, and play an important role in the electrification that is being promoted toward decarbonization. On the other hand, there needs to be careful discussions about the interpretation of the heat that heat pumps use as the heat source, which include aerothermal energy (or ambient heat), ground heat and water heat.

In the EU these forms of heat used by heat pumps have been regarded as "natural heat," defined as renewable energy and included in the statistic amount of renewable energy introduced. The EU's Renewable Energy Directive (RED) had prescribed in 2009 a method for calculating the heat volume in cases where these forms of heat are used by heating-purpose heat pumps (space heating and water heating), and in June 2022 a calculation method for cooling-purpose heat pumps (space cooling) was also established[1]. In Japan, in 2009 the Act on Sophisticated Methods of Energy Supply Structures defined ambient heat as natural heat in the same category as ground heat with the phrase "heat in the atmosphere and other heat that exists in the nature"[2], but the Act does not present a method for calculating the quantity of ambient heat used. The government councils[3] also discuss how natural heat should be categorized.

It is understandable to regard ground heat and water heat, which have temperature different to ambient temperature, as "natural heat" and defining them as renewable energy, but there will be debates on whether or not aerothermal energy, whose temperature is ambient temperature itself, should be defined as renewable energy. The author has ever concluded in 2010 that it might be possible to regard aerothermal energy used by heating-purpose heat pumps as renewable energy, while aerothermal energy should not be classified in the same category as the other renewable energy because heat pumps require electricity in conjunction with the aerothermal energy [1]. Responding to the EU's RED which subsequently presented a new definition of renewable energy in cooling-purpose heat pumps in 2022, this paper will reconstruct interpretation of natural heat by carefully examining the RED, and by comprehensively reconsidering the mechanism of heating and cooling-purpose heat pumps from a scientific point of view. Though there are two types of heat pumps, electrically driven and heat-driven, this paper targets the electrically driven type that accounts for the majority of the heat pumps in use.

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02018L2001-20220607&from=EN#tocId64

[2] "Treatment of natural heat in the revised Act on the Rational Use of Energy", Reference material 2, Working Group on Standards for Factories, Energy Efficiency and Conservation Subcommittee, Committee on Energy Efficiency and Renewable Energy, FY2022 Fourth Advisory Committee for Natural Resources and Energy

[3] For example, the 63rd Power and Gas Basic Policy Subcommittee, Electricity and Gas Industry Committee, Advisory Committee for Natural Resources and Energy

The aerothermal energy used in heating-purpose heat pumps is artificially generated

First, aerothermal energy used by heat pumps will be addressed. Heating-purpose heat pumps are targeted (cooling-purpose heat pumps will be discussed later). Heating-purpose heat pumps are mostly used for space heating for households and commercial buildings. The mechanism is that the total of the electricity input to the heat pump and the amount of heat (aerothermal energy) absorbed from the ambient air as a result of the thermodynamic cycle powered by the electricity is supplied as heat (see the left side of Fig.1). In other words, assuming that the electricity input is EL, the amount of heat absorbed from the ambient air is Q_L and the heat supplied is Q_H,

$$EL + Q_L = Q_H \tag{1}$$

The aerothermal energy is Q_L, and it is observed that the heat pump uses aerothermal energy in combination with electricity in order to satisfy the heating demand (service demand) of Q_H. In the case of heating-purpose heat pumps, the Coefficient of Performance (COP), an indicator of heat pump efficiency, is expressed as the ratio of the heat supplied to the electricity input:

$$COP_H = \frac{Q_H}{EL} \tag{2}$$

and aerothermal energy Q_L is identified from formulas (1) and (2) as below:

$$Q_L = Q_H\left(1 - \frac{1}{COP_H}\right) \tag{3}$$

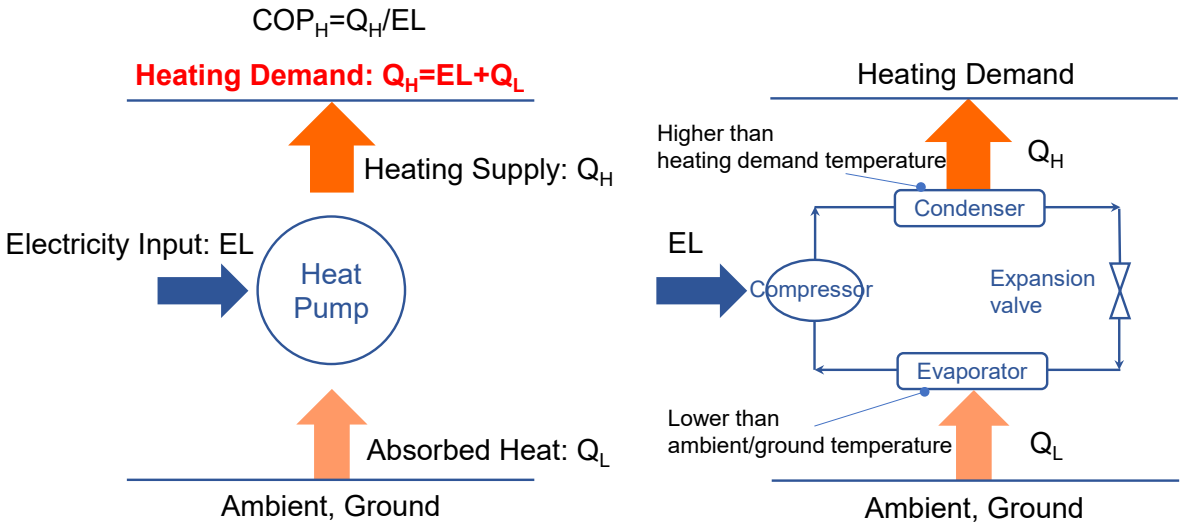

Fig. 1 Mechanism of Heating-purpose Heat Pump

The definition formula prescribed in the EU's RED is

$$E_{RES} = Q_{usable} \times \left(1 - \frac{1}{SPF}\right) \quad (4)$$

where E_{RES} is aerothermal energy that the EU's RED regards as renewable energy, Q_{usable} is the amount of heat that is supplied, and SPF is average COP_H in the overall heat supply period (season)[4]. Substituting Q_L in formula (3)'s for E_{RES}, Q_H for Q_{usable} and COP_H for SPF, it becomes formula (4). In other words, the EU's RED regards Q_L (aerothermal energy) as renewable energy.

However, there is a need to take a deep dive into why aerothermal energy, which has the ambient temperature, becomes usable. Heat becomes useable only when its temperature is different from the surroundings temperature. For example, ground heat and water heat being warmer than the ambient temperature during winter and cooler in summer have value to be used, but aerothermal energy is the ambient itself, with no temperature difference available, and consequently there is no value as it is.

Then, let us take a more detailed look at the mechanism of heat pumps (See the right side of Fig. 1). A heat pump is made up of a compressor, condenser, expansion valve and evaporator, and refrigerant circulates through these components. Thanks to electricity input, the compressed refrigerant reaches a high temperature and high pressure, then provides heat (warms a room) by releasing the heat at the condenser. The refrigerant exiting the condenser passes through the expansion valve and becomes cooler than the ambient temperature, enabling to absorb heat from the ambient at the evaporator. Having absorbed heat from the ambient air, the refrigerant is returned to the compressor and its temperature and pressure increased again. This series of steps in a cycle is repeated. The heat absorbed at the evaporator from the ambient air in this cycle is aerothermal energy.

In other words, only when the thermodynamic cycle of a heat pump driven by electricity input brings the refrigerant into a lower temperature state than the ambient air, it becomes possible to absorb heat from the ambient air. It should be noted that the aerothermal energy does not exist in nature originally. Aerothermal energy becomes usable because colder-than-ambient state (a lower temperature state) which is artificially created by a heat pump is generated within the thermodynamic cycle. Regarding this aerothermal energy as natural heat and defining it as renewable energy is akin to regarding the ice artificially produced in a refrigerator as the same as the snow or ice that exists in the nature.

Accordingly, aerothermal energy that is only utilizable in an artificially created state resulting from

[4] More specifically, the EU's RED sets a threshold for SPF, and if the heat pump with SPF above the threshold, the aerothermal energy is regarded as renewable energy.

the input of electricity does not exist in the nature and cannot be viewed as natural heat. From this standpoint, defining aerothermal energy as renewable energy is inappropriate.

Ground heat is renewable energy, but how should it be interpreted when used by heat pumps?

Next, ground heat or water heat is addressed. Naturally, ground heat, which is in winter warmer than the ambient temperature, can be used for heating, and in summer it can be used for cooling, so the whole quantity of heating and cooling used in those purposes can be counted as a quantity of renewable energy. It is in other words the direct utilization of natural heat.

On the other hand, the situation becomes a little complicated when these types of natural heat are utilized in heat pumps. Here, heating-purpose heat pumps with ground heat as an example will be discussed (cooling-purpose heat pumps will be discussed later). As was the case with aerothermal energy, formula (1) is valid. The EU's RED defines ground heat indicated by Q_L in formula (1) as renewable energy, based on the mechanism of heat pump that simply uses ground heat, same as the case of aerothermal energy.

However, theoretically, the value of ground heat stems from its temperature difference compared to the ambient air temperature. If the temperature of ground heat is the same as the ambient air temperature, ground heat is the same as aerothermal energy and has no value. Based on this logic, the quantity of heat corresponding to the difference in temperature between ground heat and ambient air should be regarded as renewable energy. To identify this quantity of heat it is helpful to look into the principle of heat pumps. Because the temperature of ground heat (in winter) is higher than that of aerothermal energy (ambient temperature) it becomes easier to supply heat to the refrigerant from ground heat (see the evaporator on the right side of Fig.1), and being able to absorb a greater quantity of heat offers the benefit of reducing the amount of electricity input to the heat pump (increasing efficiency). In other words, this is the same principle as an air-source heat pump when the ambient air temperature is high[5]. Based on this principle, the quantity of heat that ground-source heat pumps utilize as renewable energy can be identified as the difference in electricity consumption between an air-source heat pump and a ground-source heat pump (the heating demand should be same for both).

Formulas (5) and (6) below illustrate formula (1) in the case of aerothermal energy use and ground heat use, respectively (subscript A refers to aerothermal energy while subscript G refers to ground heat):

$$EL_A + Q_{LA} = Q_H \qquad \text{aerothermal energy} \qquad (5)$$

$$EL_G + Q_{LG} = Q_H \qquad \text{ground heat} \qquad (6)$$

[5] When air conditioners are used for space heating, the lower (higher) the ambient air temperature is, the lower (higher) the efficiency is, thus increasing (decreasing) the electricity consumption.

Q_H is heating demand (service demand) and is the same for both. The heat used is Q_{LA} in the case of aerothermal energy and Q_{LG} in the case of ground heat. The electricity input is E_{LA} and E_{LG}, respectively. Based on the above-mentioned logic, the value of ground heat as renewable energy is Q_{LG}e- Q_{LA}, expressed from formula (5) and (6) by EL_A - EL_G, which means that the quantity of ground heat as renewable energy is able to be identified by the difference in electricity consumptions.

The principle is that only the quantity of heat originating from the difference from the ambient temperature (the outside temperature in the case of air conditioning)[6] is usable for whatever the type of heat.

The rationality of this method for identifying the quantity of ground heat as renewable energy is corroborated when discussing cooling-purpose heat pumps.

Cooling-purpose heat pumps only use the ambient air as a place to discard heat

Next, cooling-purpose heat pumps will be addressed. Air conditioners for household space cooling are good example for cooling-purpose heat pumps. As shown in Fig.2, the flow of energy of cooling-purpose heat pumps is the same as heating-purpose heat pumps (Fig.1), but it should be noted that the objective is opposite[7]. Formula (1) is valid as it is, but unlike the case of heating-purpose heat pump where Q_H is service demand, Q_L is service demand in case of cooling-purpose heat pump as the purpose is to remove heat. Modifying formula (1) to

$$Q_H - EL = Q_L \qquad (1)'$$

it becomes easier to understand[8].

[6] However, it is necessary to bear in mind that in the case of substances like water, although there is no temperature change during phase changes, the latent heat is useable.

[7] Air conditioners are operated in reverse for heating purposes and cooling purposes, in other words, the direction of the refrigerant flow is reversed.

[8] The coefficient of performance is $COP_C = \frac{Q_L}{EL}$ and cooling demand can be expressed as $Q_L = \frac{Q_H}{1+\frac{1}{COP_C}}$.

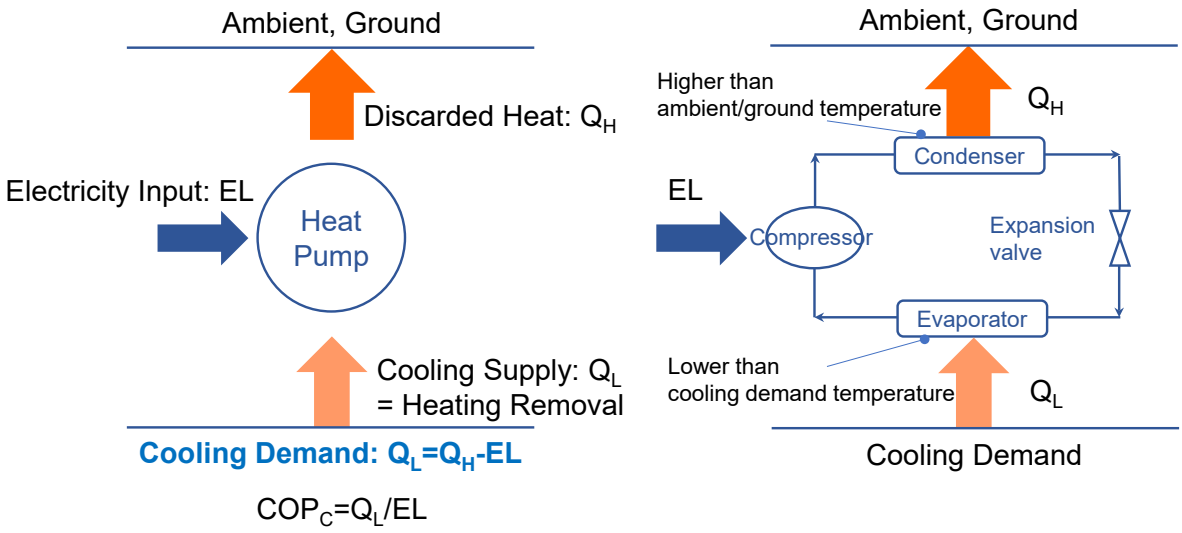

Fig. 2 Mechanism of Cooling-purpose Heat Pump

Here, how the EU's RED defines the renewable energy in cooling-purpose heat pumps will be examined. Formula (7) below is established to specify the quantity of renewable energy with regard to cooling purposes.

$$E_{RES-C} = (Q_{CSource} - E_{INPUT}) \times S_{SPFp} = Q_{CSupply} \times S_{SPFp} \quad (7)$$

where:

E_{RES-C} : Renewable energy in cooling

$Q_{CSource}$: Heat released to the environment

E_{INPUT} : Energy consumption in the cooling supply system

$Q_{CSupply}$: Supplied Cooling

S_{SPFp} : Proportion of the supplied cooling that can be regarded as renewable energy (%)

There are provisions for S_{SPFp} depending on the efficiency (SPF) of heat pumps, and more renewable energy is acknowledged for higher efficiency heat pumps., $Q_{CSource}$ in formula (7) corresponds to Q_H in formula (1)', E_{INPUT} to EL and $Q_{CSupply}$ to Q_L, which means that a part of Q_L is defined as renewable energy. However, Q_L is cooling demand (service demand) itself. In other words, in the EU's RED, when heat is removed from a certain space (a room, for example) by cooling-purpose air conditioning, some of the removed heat (taking into account the proportion S_{SPFp}) is viewed as natural heat as renewable energy. This interpretation leads to a logical inconsistency that the more cooling is supplied by consuming more electricity, the greater the volume of renewable energy is used. The EU's RED makes theoretical mistake to regard the heat removed from a room, which is the cooling demand (=

cooling load), as renewable energy.

How should the ground heat used in cooling-purpose heat pumps be interpreted?

What about cooling-purpose heat pumps that use ground heat? Because ground heat itself is indeed renewable energy, it cannot be said that these heat pumps do not use renewable energy, unlike the fact that air-source heat pumps do not use renewable energy. Nevertheless, according to the logic of the EU's RED (formula (7)), cooling demand ends up becoming renewable energy. Then, the above-mentioned logic established for heating-purpose heat pumps will be applied. In other words, in the case of cooling-purpose heat pumps, a focus is put on the fact that the efficiency (COP) increases by using ground heat that is lower (in summer) than the ambient air temperature. To regard cooling-purpose air-source heat pumps as using renewable energy is logically incorrect, but it is possible to regard the amount of electricity input reduced by improvement of heat pump efficiency through using ground heat as renewable energy. Using formula (1)' to express the case of aerothermal energy and ground heat, respectively, the formula (5)' and (6)' are established.

$$Q_{HA} - EL_A = Q_L \qquad \text{aerothermal energy} \qquad (5)'$$

$$Q_{HG} - EL_G = Q_L \qquad \text{ground heat} \qquad (6)'$$

Here, cooling demand (the quantity of heat removed) shall be same Q_L in both cases. Based on formulas (5)' and (6)', the value of ground heat as renewable energy is EL_A - EL_G (= Q_{HA} - Q_{HG}), which means that ground heat as renewable energy used by heat pumps can be identified from the difference in electricity consumption between ground-source heat pump and air-source heat pump.

Summary

The results from the above discussions are summarized below[9].

- When the heat used by heating-purpose heat pumps is aerothermal energy (the heat absorbed from the environment), the aerothermal energy being artificial heat that reaches a useable state only when electricity is input cannot be regarded as natural heat since it does not exist originally in the nature. From this point of view, it is inappropriate to define aerothermal energy as renewable energy. It is rational to regard the heat corresponding to the temperature difference between the heat used (ground heat, water heat etc.) and the ambient as renewable energy. When the heat used by heat pumps is ground heat, it can be regarded as renewable energy, but the quantity of ground

[9] It goes without saying that when ground heat is used directly, the total quantity of ground heat is renewable energy. If for example a room temperature is 30℃ while the ambient temperature is 25℃, and ambient air is fed to cool the room, the aerothermal energy can be regarded as renewable energy based on the fact that there is temperature difference. However, in reality it is almost impossible to identify this quantity.

heat as renewable energy should be defined as the difference in electricity consumption between an air-source heat pump and a ground-source heat pump, in other words electricity consumption reduction gained through improvement of heat pump efficiency by using ground heat.

- The function of cooling-purpose heat pumps is to remove heat from a certain space and discard the removed heat to the environment. Although the EU's RED defines a portion of this discarded heat as renewable energy, the discarded heat is cooling supply that is cooling demand itself, and not the utilization of natural heat exploiting the differences from the ambient air temperature. From this point of view, it is incorrect to regard cooling demand as renewable energy. The definition formula in the EU's RED leads to a logical inconsistency that the more cooling is supplied by consuming more electricity, the greater the volume of "renewable energy" is used. On the other hand, if ground heat is utilized, similarly to the case of heating-purpose heat pumps, the quantity of ground heat as renewable energy can be defined as the difference in electricity consumption between an air-source heat pump and a ground-source heat pump, in other words electricity consumption reduction gained through improvement of heat pump efficiency by using ground heat.

It is possible to estimate the quantity of natural heat such as ground heat that a heat pump uses provided that the information below are known; ambient air temperature, heating or cooling demand temperature, electricity consumption by an air-source heat pump, efficiency (COP), ground heat temperature, and relational expressions between efficiency (COP) and ambient air temperature and demand temperature.

It is also possible to estimate the quantity of aerothermal energy utilized by heating-purpose heat pumps and to add this quantity to renewable power generation like solar photovoltaic and wind power for the purpose of increasing the statistic amount of introduced renewable energy. Even if the aerothermal energy utilized in heating-purpose heat pumps is regarded as "renewable energy" and is added to renewable energies such as solar photovoltaics and wind power to statistically increase the quantity of renewable energy introduced, it is needless to say that the volume of energy consumed and CO_2 emitted by a country or region as a whole does not change. This is because the energy saving effects of the heat pumps that are in operation are already being reflected in a country or region's overall current energy consumption and CO_2 emissions. Consequently, defining the aerothermal energy used by heat pumps as renewable energy and adding it to the quantity of renewable energy introduced ostensibly inflates renewable energy statistics. However, because that aerothermal energy does not have the effects that renewable energies like solar photovoltaic and wind power possess, such as reducing CO_2 emissions and enhancing the self-sufficiency rate, there is a possibility that an intermixed element would be introduced into the original goals of renewable energy policy.

Furthermore, in the case of cooling-purpose heat pumps, they do not utilize aerothermal energy, and only supply cooling as a result of electricity consumption by the heat pumps.

Heat pumps are excellent high-efficiency equipment (energy-saving equipment). Increasing the uptake of high-efficiency (as primary energy basis) heat pumps can be expected to have energy consumption and CO_2 emissions reduction impacts. Heat pumps should be promoted on the basis of scientific verification focusing on the intrinsic contributions that renewable energy possesses for reducing CO_2 emissions and enhancing the self-sufficiency rate, rather than focusing on numerical target of renewable energy.

Reference

[1] Yoshiaki Shibata, “Aerothermal Energy Use by Heat Pumps in Japan,” IEEJ October 2010, IEEJ

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