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PRELIMINARY RESOURCE ASSESSMENT OF HOT SPRING POWER GENERATION IN JAPAN

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ABSTRACT

The Kalina cycle power generation system with the ammonia-water solution has expanded the geothermal power generation to the low-temperature hydrothermal resource region such as the hot spring water. Taking account for such the current low-temperature power generation system, a preliminary resource assessment of the 4,536 hot spring data in Japan is done. A map of the thermal output of the hot springs gives valuable aspects distinctive from the map of the discharge temperature, and suggests many candidate areas for the future small-scale geothermal power development not only from the volcanogenic hot springs but also from the non-volcanogenic hot springs. The total thermal output exceeding 25 ˚C from these hot springs in Japan is calculated to be 4,557 MWt. If the total recovery factor of energy from the Kalina cycle is assumed to be 5 %, the electricity generation of 228 MWe can be roughly estimated from these hot springs in Japan.

Keywords: hot spring, low enthalpy geothermal resources, Kalina cycle, resource assessment, geothermal power generation, Japan

1. INTRODUCTION

Geothermal power generation capacity has dramatically increased to 530 MWe in Japan until the year 1998, but after then, incentive policy to geothermal development has been withdrawn by government, resulting in that the geothermal industry abruptly faces a severe stage in Japan. Likewise, most of governmental geothermal R&D projects have also been terminated by the negative evaluation to the geothermal R&D policy in 2001. As a result, only one ongoing governmental geothermal project in Japan is the Geothermal Development Promotion Survey by the New Energy and Industrial Technology Development Organization (NEDO). The objective of this project has been changed from the previous large-scale geothermal power development to the relatively small-scale one since 2004, because this is only a possible choice under the less incentive policy circumstances.

The small-scale geothermal power development has, however, many advantages in terms of the special geothermal condition in Japan. There are two specific obstacles against the large-scale geothermal development in Japan: one is national parks that cover many Quaternary volcanoes as well as about 60 % of high-temperature geothermal resources where geothermal development is basically prohibited, and the other is a huge number of hot spring resorts where hot spring owners tend to oppose to the geothermal development. When the objective is changed from the large-scale to small-scale geothermal development, the objective fields are expanded to wider areas away from the national parks. The small-scale geothermal development also opens a new horizon that the hot spring owners themselves can develop their own power generation systems.

Current technology of the binary cycle geothermal power generation system such as a Rankin cycle and Kalina cycle enables us to develop the small-scale geothermal power plants. Particularly, the binary Kalina cycle expanded the power generation sources to most of the temperature range of hot springs.

To spread the small-scale geothermal power development over Japan, this paper tries to assess the potentials of hot springs as a geothermal power generation resource in Japan.

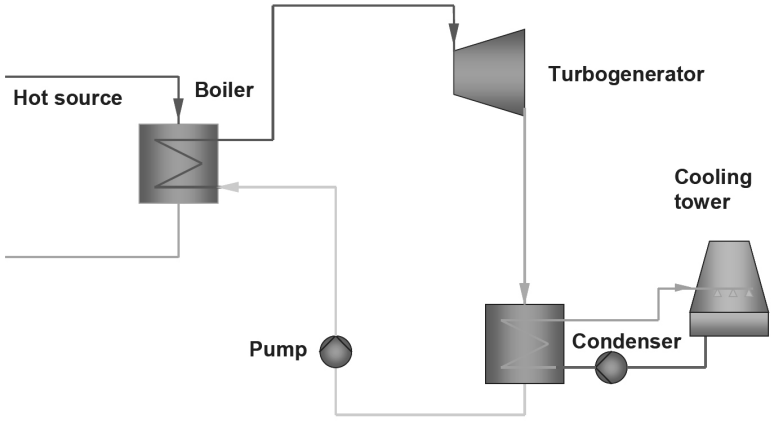


Figure 1. Typical organic Rankin cycle power generation system (Valdimarsson and Eliasson, 2003).

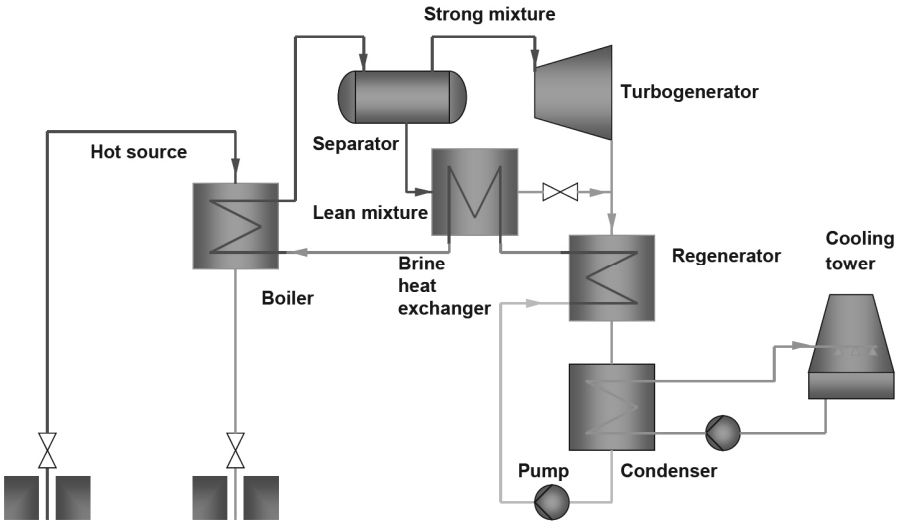


Figure 2. Typical Kalina cycle power generation system (Valdimarsson and Eliasson, 2003).

2. CATEGORIES OF GEOTHERMAL RESOURCES AND A KALINA CYCLE

Geothermal fluid resources are commonly classified into three categories by the temperature thresholds (Muffler and Guffanti, 1979): high-temperature (>150 ˚C), intermediate-temperature (90-150 ˚C) and low-temperature (<90 ˚C) hydrothermal convection systems. The high-temperature hydrothermal resource is adequate for the traditional flash-type geothermal power generation. Geothermal power generation has long been possible only in this category. Afterwards, the binary Rankin cycle power generation system with organic fluids such as chlorofluorocarbon and isopenthane has been developed as shown in Figure 1, and this system has expanded geothermal power generation to the intermediate-temperature geothermal resource.

Dr. Alex. I. Kalina has newly designed a Kalina cycle, an efficient power generation cycle with an ammonia-water mixture in 1980 (Kalina, 1984) as shown in Figure 2. This is a sort of the binary cycle power generation system where the operating fluid has a varying boiling point temperature. The phase diagram of the ammonia-water mixture is somewhat similar to the phase relation of the plagioclase solid solution, but the difference is a liquid solution of ammonia and water as end members as shown in Figure 3. This nature provides the efficient energy recovery 10 to 20 % higher than the conventional Rankin cycle (Kalina, 1984). When the initial ammonia-water ratio is changed, the ratio of the vapor and liquid will be changed. This nature promises a flexible application of the system to the varying temperature thermal sources.

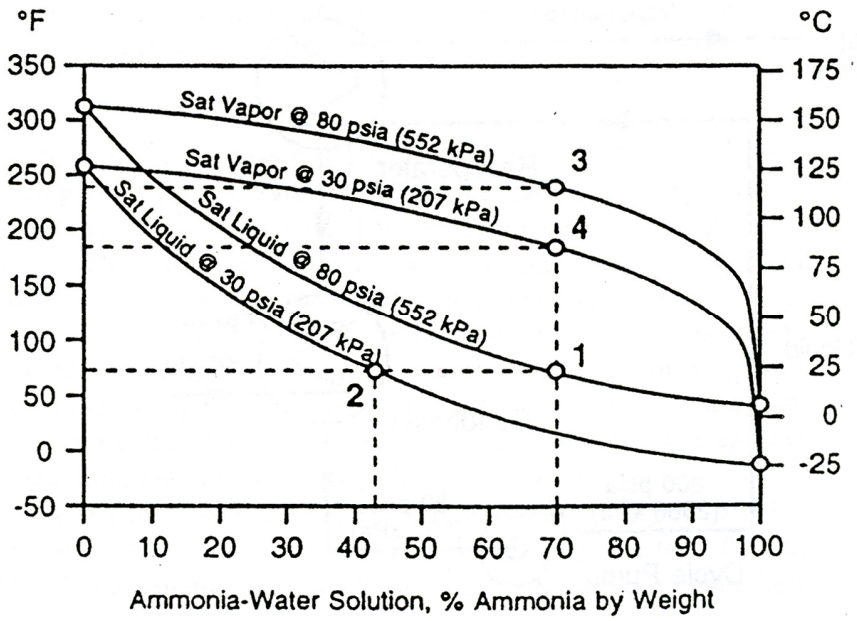


Figure 3. Phase diagram of the ammonia-water mixture (Mlcak, 1996).

It is worthy to note that the Kalina cycle power generation system with ammonia-water solution theoretically enables to generate electric power from very low-temperature heat source even less than 0 ˚C as shown in Figure 3. However, when we consider that the operating fluids are usually cooled by the natural air or water, an atmospheric temperature could be the lower limit of the thermal source outlet for the cycle. The average atmospheric temperature is 25 ˚C in Japan during the summer season. Even if the operating fluid temperature is 25 ˚C, Figure 3 shows that the mixture of 98 % ammonia and 2 % water still produce 100 % vapor at the pressure of 207 kPa. Therefore, the Kalina cycle has possibility to generate electric power from the low-temperature geothermal resource such as the most of temperature range of hot spring water higher than 25 ˚C. This system has thus expanded geothermal power generation to the low-temperature geothermal resource.

Another important fact is that most of elementary technology required for the Kalina cycle has already been established in the refrigeration industry field for over 100 years before the appearance of the Kalina cycle. Actually, the Kalina cycle power generation is practically using in the co-generation field and wasting heat power generation field.

3. DATA SET OF HOT SPRINGS IN JAPAN

Kimbara (1992) has collected 3,865 hot springs data from all over Japan on the name, location (on the 1:400,000 scale map), discharge temperature (˚C), discharge rate (l/min, not all), chemical type of water and pH. After then, locations of these hot springs were digitized by Kimbara (1996) and contoured by Yano et al. (1999). Moreover, Kimbara has collected additional 671 hot springs data from Japan and all the 4,536 data are under the preparation for publication on CD-ROM (Kimbara and Hasegawa, in preparation). We here use the data set of 4,536 hot springs in Japan.

Among the 4,536 hot spring data, 74 hot springs have no discharge temperature records. Therefore, the rest 4,462 hot spring data are used here. Hot springs are defined by the Hot Spring Law to be higher than 25 ˚C in the discharge temperature or higher than the given concentrations in the several specific chemical components in Japan. The hot springs defined only by the latter criterion should be rather called mineral springs, but are legally defined as the hot springs in Japan, considering of the balneological value. They are 25 ˚C or less than the temperature and are not interesting from the geothermal point of view. Among the 4,462 hot springs, 1,868 springs belong to this category and are 25 ˚C or less than the temperature.

Figure 4 shows the histogram of the discharge temperature of the 4,462 hot springs. The number decreases to the low-temperature end below 25 ˚C. This reflects that huge numbers of groundwater spectrum exist in this range but only mineral springs are extracted from them. In other words, the deceasing trend is ascribed to the sampling bias and limit. Other part is broadly characterized by a power function with a fractal dimension. However, an important exception is observed in the

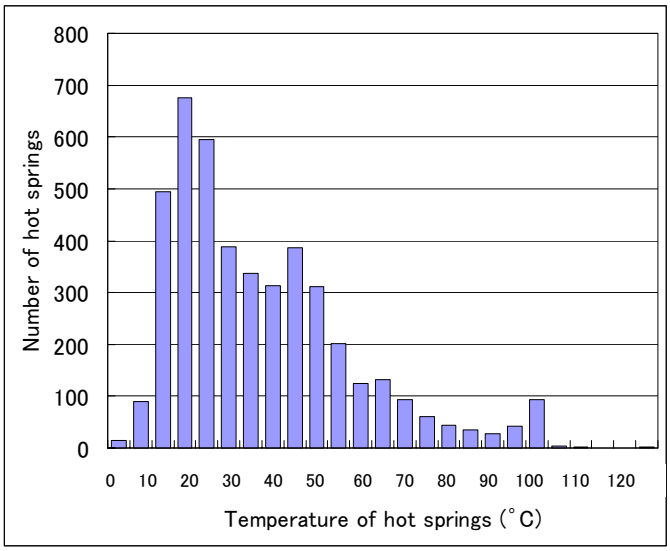


Figure 4. Histogram of discharge temperature of the 4,462 hot springs in Japan.

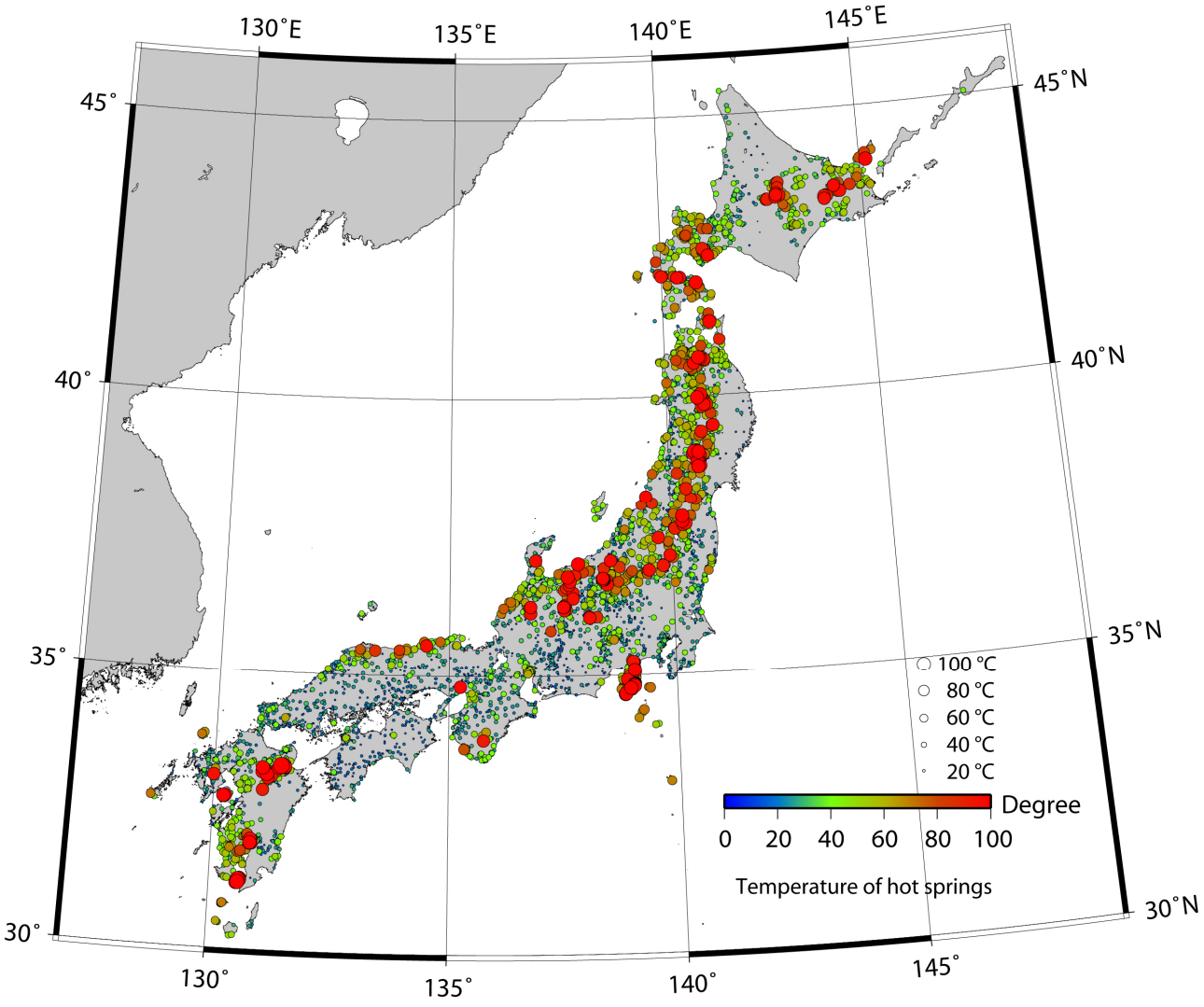


Figure 5. A map of the discharge temperature of the 4,462 hot springs in Japan.

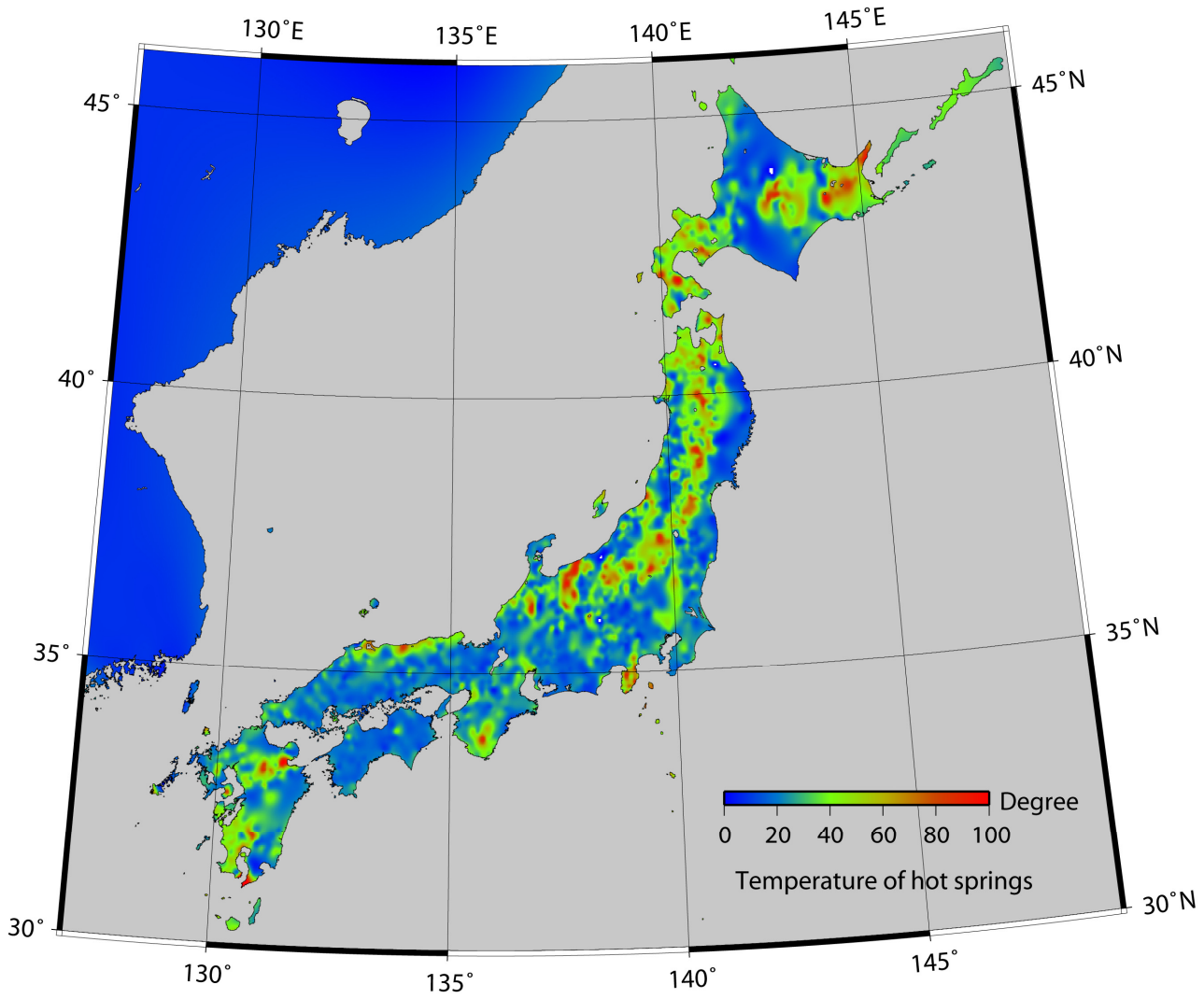


Figure 6. A contour map of the discharge temperature of the 4,462 hot springs in Japan.

increasing number from 90 ˚C to 100 ˚C. This is probably ascribed to the effect of the dynamic up-flows of the high-temperature fluids by the boiling. Once the fluids reach the boiling point, they are buffered by the energy consumption to vaporize. The small number of the hot springs higher than 100 ˚C is ascribed to the buffer and the leakage by the increasing vapor phase.

Many of the hot springs were developed by the drill holes, sometimes by the deep wells as deep as the 1.5 km depth, and therefore, the discharge temperature of these hot springs are not evenly compared without their depth evaluation for the purpose of the geothermal gradient. The depth data were also collected from some of them, but were not completed.

Whether the hot springs are natural springs or drill hole discharge water, it is obvious that they are already available heat sources at the surface. If the water is assumed to be solely used for the Kalian cycle power generation, we can obtain some amount of electricity from the power generation. At this moment, these hot springs are almost entirely used for bathing, where heat consumption is very small, and nevertheless, the used water is entirely wasting. Therefore, if we use the water before and after the bathing, we may obtain most of heat contents for the power generation without serious damage to the purpose of bathing and hot spring tourism. An assessment of these potentials is the objective of this paper.

Discharge temperatures of these hot springs in Japan are plotted on Figure 5. The map projection system is the Lambert Conic.

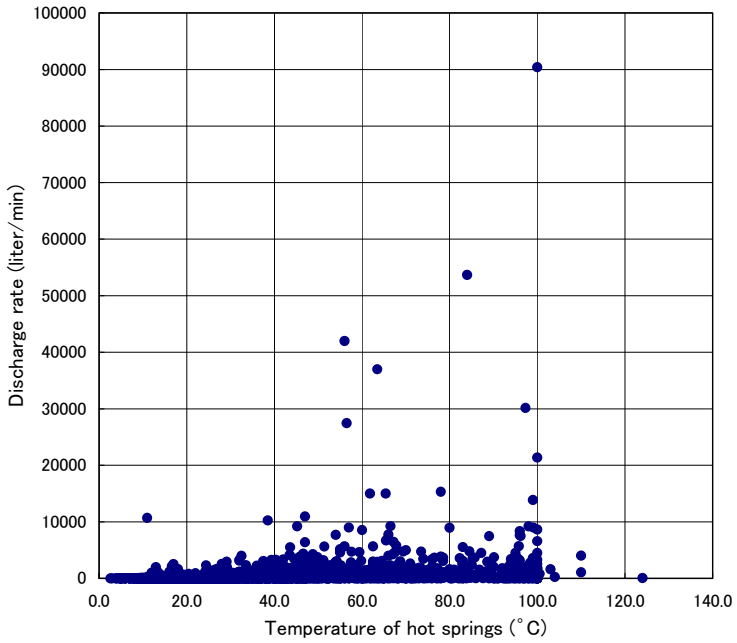


Figure 7. Relations between the discharge temperature and discharge rate of the 4,462 hot springs in Japan.

Conformal Projection and its median is placed on 136 °E and 36 °N. The 4,462 hot springs are plotted on Figure 5, including the 1868 mineral springs that are still useful to indicate the low-temperature area. Both the color and diameter of circle are proportional to the discharge temperature on this figure. Most of the high-temperature hot springs are obviously observed near Quaternary volcanoes. The highest temperature of the hot springs is 124 °C where the diameter of the circle is proportionally enlarged, but the color of the hot spring is saturated at 100 °C in Figure 5.

4. MAP OF HOT SPRING RESOURCE AREA IN JAPAN

A contour map of 4,462 hot springs are shown in Figure 6. The map projection system is the same as Figure 5. The grid space is given to be 0.025 degree on the earth. Contours are calculated by the minimum curvature method by the algorithm described in Smith and Wessel (1991) on the GMT software (Wessel and Smith, 1998). This algorithm can change a tension factor T from 0 to 1, incorporating smoothing effect by a spline function, but T is here given as 0 in Figure 6 that is the minimum curvature method in a narrow sense.

This map is almost the same as the map made by Yano et al. (1999), but the additional 671 data give slightly detailed information in some areas.

As mentioned above, this map is not the equal-depth temperature map. However, whether the source depth is shallower or deeper, this map shows the distribution of confirmed hot spring water discharges in Japan. Therefore, this map can be used as a practical indicator for the localization of the intermediate- to low-temperature geothermal resources for small-scale power generation in Japan.

5. MAP OF THERMAL OUTPUT OF HOT SPRINGS IN JAPAN

Spatial distribution of the hot spring (intermediate- to low-temperature geothermal) power resources in Japan is obtained in Figure 6, but this map does not show the thermal output of the hot spring resources. One way to calculate thermal output may be done by the integration of high-temperature anomaly areas from Figure 6, under the assumption of an average discharge rate to the unit area. However, there is no a priori reasoning that the discharge rate can be averaged. The thermal output should better be evaluated from the discharge rate of each hot spring.

Unfortunately, discharge rate records are only available from 3,702 hot springs among the 4,462 hot springs in Figure 5, and

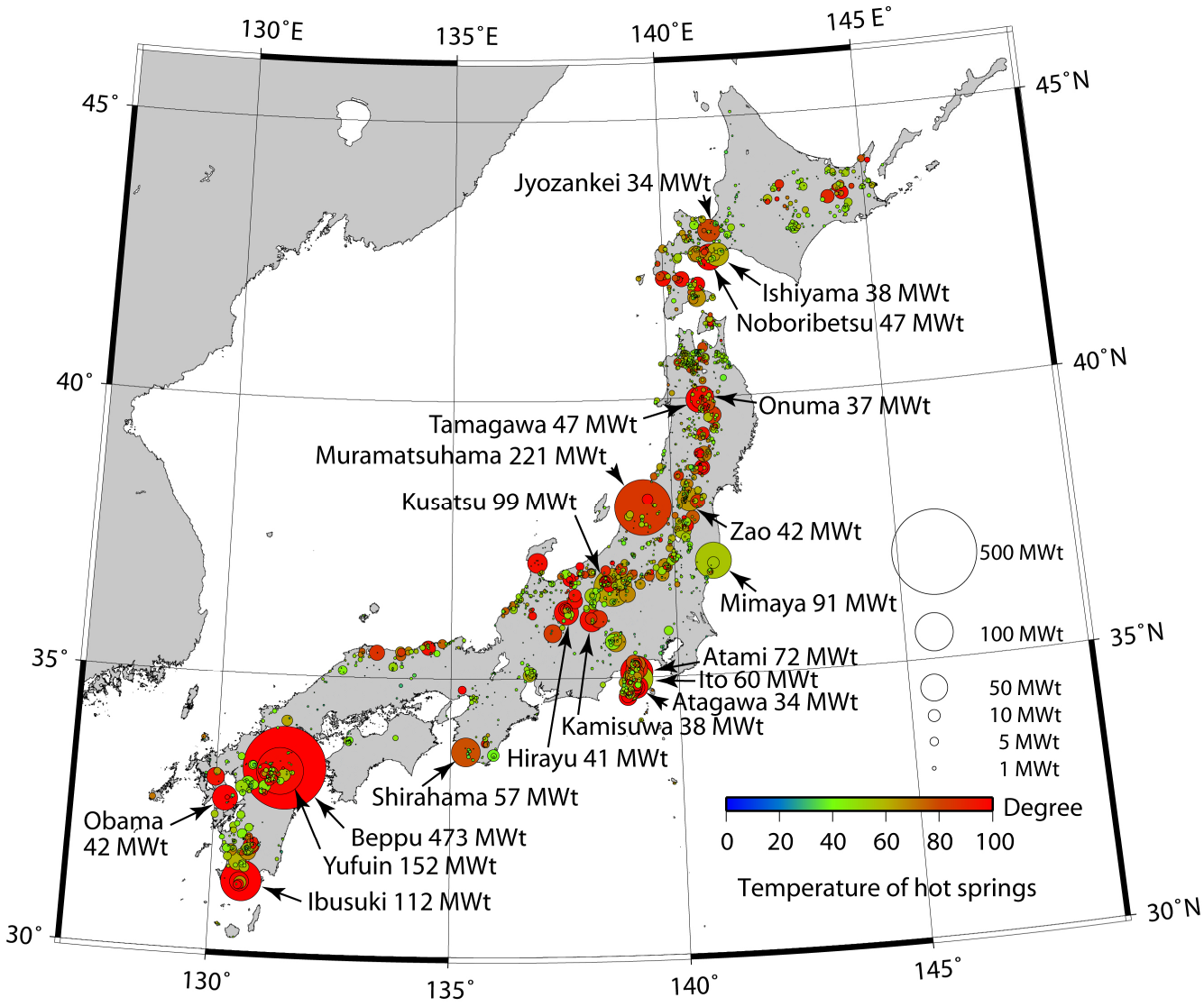


Figure 8. A map of thermal outputs of the 4,462 hot springs in Japan.

the rest 760 hot springs have no discharge rate records. Therefore, a minimum value 1 liter/minute is given to the 760 hot springs from the most conservative point of view. The discharge rate is compared with the discharge temperature in Figure 7. Although the number of the hot springs broadly decreases to the high-temperature end (Figure 4), the variation range of the discharge rate increases to the high temperature end (Figure 7). Therefore, a positive correlation is roughly found between the discharge temperature and discharge rate. This is ascribed to the velocity of thermal convection due to the thermo-gravitational buoyancy effect in the higher-temperature range.

As discussed above, the lower-temperature limit of the heat source for the Kalina cycle could be 25 ˚C due to the realistic cooling process. Thermal output is then calculated from the temperature range above 25 ˚C. This leads that the 1868 mineral springs are neglected and only the rest 2,594 hot springs are accounted in consideration.

Thermal outputs of hot springs are shown in Figure 8. Thermal output of each hot spring is calculated from the method that the temperature value exceeding 25 ˚C is multiplied by the discharge rate. The unit of thermal output is converted from cal/min to kW. For the quantitative visualization, the gross area of each circle is made proportional to the thermal output in the kW unit in this figure. Thermal potentials can be evenly evaluated from the size of the circle, regardless of the discharge temperature shown by the color. As shown in this figure, the thermal output of hot spring tends to be much more biased in the high-temperature hot springs compared to the map of Figure 5. This is resulted from a synergy effect both of the discharge temperature and discharge rate. For example, the thermal output in volcanic front is more significant than in back-arc volcanic chain (Figure 8) compared to Figure 5. An exception is the Muramatsuhama hot spring in Niigata Prefecture that has the second largest potential in Japan.

Another remarkable feature is that the junctions of the volcanic arcs are always characterized by the large thermal outputs such as Noboribetsu in western Hokkaido, Suwa-Kusatsu in north-central Japan, Izu Peninsula in south-central Japan and Beppu in northern Kyushu. The Shirahama hot spring in southern Kii Peninsula and the Mimaya hot spring in eastern Fukushima Prefecture are not volcanogenic hot springs, but their potentials are comparative with major volcanogenic hot springs.

6. DISCUSSION AND CONCLUSIONS

As described above, this paper preliminarily tries to assess the power generation potentials of discharge water of hot springs in Japan, particularly taking it account for the small-scale geothermal power generation such as the Kalina cycle. For the purpose, a data set of 4,536 hot springs in Japan is analyzed. A map of the discharge temperature of hot springs is summarized in Figure 5 and a map of the spatial extent of the intermediate- to low-temperature geothermal resources is summarized in Figure 6. These maps imply the temperature condition when the shallow-depth hole will be drilled at some place in Japan. However, they do not suggest the thermal outputs for the small-scale geothermal power development. Although the discharge rate data are still not completed all over Japan, a map of the thermal output of the hot springs is preliminarily constructed in Figure 8. This map proposes much different aspects from Figures 5 and 6, and suggests many candidate areas for the future small-scale geothermal power developments not only from the volcanogenic hot springs but also from the non-volcanogenic hot springs.

This paper is only at an initial stage of the comprehensive assessment and further quantitative analyses are required. However, the total thermal output from the hot springs in Figure 8 is calculated, and a value 4,557,197 kWt or 4,557 MWt is obtained. Lund and Freeston (2001) estimated the Japanese direct use of geothermal energy to be 1,167 MWt that include not only bathing and balneology but also space heating and snow melting where all the waters are ultimately supplied from the hot springs or hot spring wells. They calculated only the energy consumption between the inlet and outlet temperatures even in the bathing use, a largest part of the direct use in Japan. Therefore, their estimation 1,167 MWt, that is 25 % of the present 4,557 MWt, is quite consistent with the present study. Actually, the rest 75 % of unused portions of thermal energy of the hot springs between 4,557 MWt and 1,167 MWt would be the objective for such the future Kalina cycle utilization.

There are not many reports on the recovery factor between the external thermal energy source inlet and electricity outlet of the Kalina cycle. One of the valuable reports is a Kalina cycle power generation system installed in the Kashima Steelworks, Ibaraki Prefecture in Japan, where the wasting heat from the factory has been utilized since 1999. The system consumes 1300 t/h of 98 ˚C water as a heat source and its outlet temperature is 76 ˚C. This energy is calculated to be 33,240 kWt, whereas the electricity generation is 3,507 kWe as an actual production (NEDO, 2002). The recovered electricity is 10.6 % to the supplying energy source inlet. Sea water of 18 ˚C is used as a cooling medium in this system, nevertheless, the source water outlet is still 76 ˚C.

Considering of such difficulty in the cooling efficiency, we assume that the low-temperature half of the thermal energy of the hot springs is difficult to be recovered. The total recovery factor is then assumed to be 5 %. In this very conservative assumption, the total electricity generation of 228 MWe can be roughly estimated from the present hot spring data in Japan. This is small compared to the large-scale geothermal development, but is still large as a production value without drilling and can be easily enlarged by the incorporation of shallow-depth drilling like the hot spring development.

APPENDIX: NOTE ON THE FREE SOFTWARE GENERIC MAPPING TOOLS (GMT)

All the mappings of hot springs of this paper have been performed by the Generic Mapping Tools (GMT). Most geoscientists take a long time to illustrate a map for reports and articles. To expedite this process, the software Generic Mapping Tools (GMT) was released as a free software package that can be used to manipulate columns of tabular data, time-series, and gridded data sets, and display these data in a variety of forms ranging from simple x-y plots to maps and color, perspective, and shaded-relief illustrations. GMT software was originally written as a set of UNIX tools by Wessel and Smith (1998) but is now utilized on Windows and MacOS. A short guide for the Window users is given here.

All the files for the Windows users can be downloaded form the following site.
ftp://gmt.soest.hawaii.edu/pub/gmt/

Most comprehensive manual is available from the following site.
http://gmt.soest.hawaii.edu/

All the maps are generated as a file with the extension ".ps". To open the ".ps" files, a free software GSview is required. This can be downloaded from the following site.
http://www.cs.wisc.edu/~ghost/

However, the ".ps" files can also be opened by Adobe Illustrator. Installation of GMT on the Windows environment is slightly frustrative, but the following site will be helpful.
http://home.hiroshima-u.ac.jp/kojiok/gmtwinst.html

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