

A Linear Fresnel concentrating Solar PVT System Design and Test in Korea

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ABSTRACT: A non-imaging linear Fresnel concentrating photovoltaic system with geometric concentration ratio of 5.7 is designed and tested at KIER in Daejeon, South Korea. The optical efficiency of the concentrator was 57% at an effective concentration ratio of 3.2. Only 57% of the concentrating light was illuminating the PV module, therefore, the optical efficiency and effective concentration ratio were lower than the expected values. Furthermore, the lateral distribution of the temperature suggested the non-uniformity of concentrating light possibly due to misalignment or variation in the contour of Fresnel lens along its length. Outdoor current and voltage measurements showed that efficiency reduced from 21.8% to 14.4% under the concentration and resulting higher operating temperatures. The electrical power output of the PV module under Fresnel lens with tracking the sun measured across a load resistance was approximately 4 times higher than the fixed PV module without the Fresnel lens on clear sky winter days in Daejeon, South Korea. The experiences gained from the experiments on the non-imaging linear Fresnel lens concentrator PV will be the first towards developing a large non-imaging linear Fresnel lens concentrating PV system to improve the concentrating PVT system performance in Korea.

Keywords: linear Fresnel, photovoltaic thermal (PVT), concentrator, concentration ratio, sunlight

1. INTRODUCTION

Relatively higher electricity generation costs of photovoltaic (PV) due to the use of expensive photovoltaic raw materials is one of the barriers to its wide spread utilization as a clean and environmental friendly electricity source. One option to overcome this cost barrier is the use of optical concentrating technologies costing only about 1/20th of PV materials [1]. Large conventional glass lenses are bulky, heavy and costly making them impractical for large area concentrating applications.

However, Fresnel lenses are made by projecting the lens surfaces onto a plane or curved sheet in a way that rays encounter the same slopes as in the conventional lens and, therefore, are similarly refracted [2]. Consequently, Fresnel lenses are lighter in weight and less expensive and can be used in concentrating PV applications [1-5]. Fresnel lenses can focus the light onto a point or along a line depending on the design geometry. Thus, Fresnel lens can be used in point focus geometry where it concentrates sunlight on a small single solar cell whereas linear Fresnel concentrating

configuration is used for concentrating light on an array of solar cells.

Non-imaging Fresnel lens concentrators for medium concentration photovoltaic applications have been designed, manufactured and a comparative cost analysis reported [3].

Photovoltaic cells of small area with high energy conversion efficiency are required under concentrating sunlight. However, it is not a problem as an energy conversion efficiency of 39.0% at 236 suns has been reported by Spectrolab Inc. USA compared to commercially available solar cells for flat PV modules which can have efficiencies from 5% to 20% [6]. The other important factor that can affect the performance of PV modules under concentration is the operating temperature as higher temperatures can reduce the energy conversion efficiency of PV cells [7]. The cooling of the solar cells becomes even more important to maintain the solar cell operating temperatures low as the concentration level of sunlight is increased. Operating the PV cell at high temperature can cause irreversible damage and make it unusable [8]. The concentrating solar cell module can be cooled down passively provided that solar cell temperatures do not reach more than 80°C at peak solar radiation and stagnation conditions [9], however, a temperature limit of 120°C for high quality cells has also been suggested [3]. Each PV manufacture provides the temperature limit for its concentrating PV cells and those limits should be observed to avoid permanent damage. A linear Fresnel concentrating solar PVT system has been designed and tested in KIER. This paper introduces the how concentrating linear Fresnel PV system and experiment results.

2. LOW CONCENTRATING LINEAR FRESNEL PV SYSTEM

The essential components of the concentrator photovoltaic system were a

non-imaging linear Fresnel lens, photovoltaic module, a support structure which can be rotated manually along two axes to track the sun and the measurement system. The Fresnel lens is made by bending a 100 cm wide and 149cm long Lensfilm SCL-1000 into a convex lens shape along its length. The concentrator with an aperture width of 84.8cm can be used for concentrating sunlight on a PV module width of 4cm or less with 21X concentration. However, the concentrator aperture is 88cm and PV module used is 10cm wide and, hence, not suitable for only 21X concentration as only a fraction of PV cells on the module will be illuminated. This type of situation will cause strains in the module due to sharp temperature gradient. Furthermore, the shading will increase the series resistance or reverse bias the PV cells and hence will reduce the output electrical power [11]. In order to avoid such detrimental effects, the position of the PV module was adjusted so that the concentrated solar radiation will be illuminating the whole width of the module resulting in a geometrical concentration ratio lower than 6X. The two photovoltaic modules were fabricated using 24 quarter sized single crystalline Sunpower type A-300 solar cells each connected in series. Each module was 10cm wide and 105cm long with an effective area of 0.088m². Solar radiation was recorded using LICOR silicon photodiode pyranometer fixed on the PV module with Fresnel lens assembly. The schematic diagram of the measurement system is shown in figure 1.

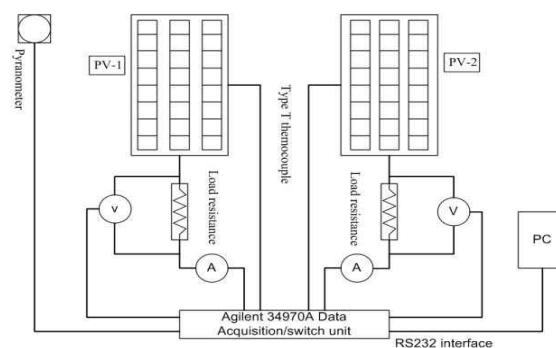


Figure 1: Schematic diagram of the measurement system.

Global and diffused solar radiations on horizontal surface and beam radiation normal to the surface were measured using Kipp & Zonen pyranometers. The current and voltage were measured across a load resistance of 5ohm rated at 300W. The measurement system consists of an Agilent 34970A data acquisition/switch unit (Agilent Technologies, USA). T-type thermocouples fixed at three different locations at the back of each module were used to measure the temperatures at three different positions at the backside of the PV module. Type ‘T’ thermocouples were also used to measure the ambient temperature. Application specific software was used to record the inputs such as load currents, voltages, solar radiation and temperatures every one minute. The photograph of both PV systems is shown in figure 2.

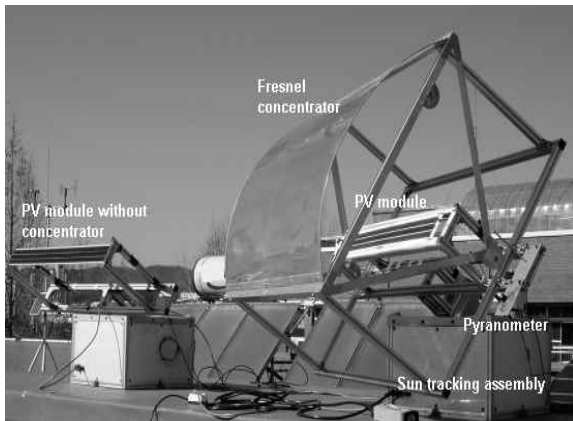


Figure 2: Picture of PV systems with and without non-imaging linear Fresnel concentrator.

The figure shows the non-imaging linear Fresnel concentrator, support structure and pyranometer. Passive cooling of the PV module under concentration was utilized as the ambient temperature during the measurement was about 0°C and maximum temperature of PV module was less than 80°C during the measurement. However, an active cooling mechanism will be used during the summer to avoid permanent

damage to PV module due to higher operating temperatures.

3. EXPERIMENTAL RESULTS

3.1 Optical Efficiency and Optical Concentration Ratio

The optical efficiency of the concentrator is the ratio of the power incident on the PV module to the power at the concentrator. It can be represented in terms of the effective averaged irradiance at the PV module (G_x), the irradiance available onto the concentrator (G), and the geometric concentration ratio (X_g) as [12]:

$$\eta_{op} = G_x / X_g G \quad (1)$$

The effective averaged irradiance at the PV module can be expressed in terms of photo-generated current as:

$$G_x = I_L(X) G / I_L \quad (2)$$

Where, $I_L(X)$ and I_L represent the photo-generated current with and without concentration. The short circuit current of PV module is directly proportional to the concentration ratio; therefore, the ratio of the short circuit current under concentration ‘ $I_{sc}(X)$ ’ and short circuit current without concentration ‘ I_{sc} ’ will give the effective concentration ratio as expressed by:

$$X = I_{sc}(X) / I_{sc} \quad (3)$$

The photo-generated current can be approximated to be equal to the short circuit current. The geometric concentration X_g is the ratio of the concentrator net aperture area A_{conc} and the PV module area A_{PV} and is expressed as:

$$X_g = A_{conc} / A_{PV} \quad (4)$$

In the case where the measurement temperature is high under concentration as compared to the reference measurement conditions, the short circuit current may

require to be corrected using the following expression [12]:

$$I_{sc}(T_x) = I_{sc,0} + \alpha_I (T_x - T_0) \quad (5)$$

Where α_I is the temperature coefficient of the short circuit current and T_x is the PV module temperature under concentration. $I_{sc,0}$ and T_0 are the short circuit current and PV module temperature at the reference measurement conditions.

The aperture of the non-imaging linear Fresnel lens was 88cm with an aperture width of 15.5cm on the PV module. Thus, the resulting geometrical optical concentration ratio is 5.7. The optical efficiency of the concentrator was 57% at this geometrical concentration ratio whereas the effective concentration ratio using equation (3) was calculated to be 3.2. The lower optical efficiency and hence effective concentration ratio in the present case can be due to variation in the contour of the Fresnel lens, and nonalignment of the concentrating system. Furthermore, the effective PV module width is 8.5cm which is smaller than the concentrator aperture of 15.5cm at PV module. Therefore, only 57% of the concentrated sunlight is contributing to the electricity generation.

3.2. Lateral Distribution of PV module Temperature

The temperature distribution along the length of the PV module under concentration can also provide information about the distribution of the concentrated sunlight; therefore, temperature was measured at three different positions at the backside of the PV module as is shown in figure 3 during the day of January 23, 2006. The positions of the type 'T' thermocouples at the backside of the PV module are also shown in the figure.

The temperature along the length of the module is not uniform as the temperature on the right hand side is 5°C higher than other positions whereas the temperature at the centre is the lowest. The difference in the

temperatures can be due to the non-uniformity of the concentrated radiation on the PV module arising from the deviation of the Fresnel lens surface geometrical symmetry.

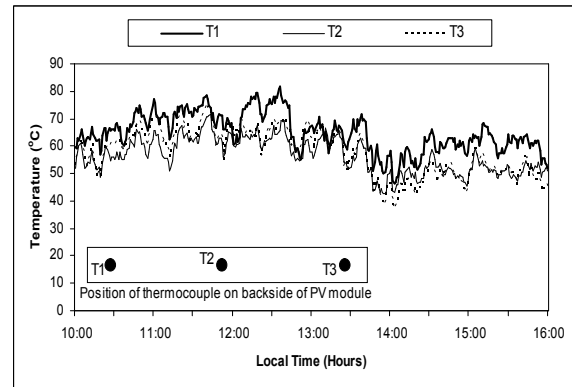


Figure 3: Lateral distribution of PV module temperature under concentration during the day of January 23, 2006.

3.3. Current-Voltage Characteristics

Current voltage curves of PV module provide the key finger prints about the quality of a PV module. The PV module was tested in out door conditions on a clear sky day of February 13, 2006 in Daejeon, South Korea between 13:15 and 14:15 hours with and without concentrator. Current-voltage characteristics of the PV module used in the study were recorded using a variable resistance rather than an I-V curve tracer. The resistance was varied manually from its minimum value to maximum whereas the data was recorded with the data logging system. The temperature of the module was allowed to stabilize within $\pm 1^\circ\text{C}$ during the 35 seconds required for the measurements. Furthermore, the variation in the solar radiation during the measurement period was $\pm 2\text{W}\cdot\text{m}^{-2}$. The module was manually positioned such that it was facing directly towards the sun. The I-V curve of the module without the Fresnel lens at 25°C and total global radiation $800\text{W}\cdot\text{m}^{-2}$ is shown in figure 4.

The output power as the function of voltage is also shown in the same figure. The power at the maximum power point was

15.3W. The fill factor and efficiency were 0.7 and 21.8% respectively. Current voltage characteristics of the same PV module under non-imaging linear Fresnel lens concentrator is shown in figure 5.

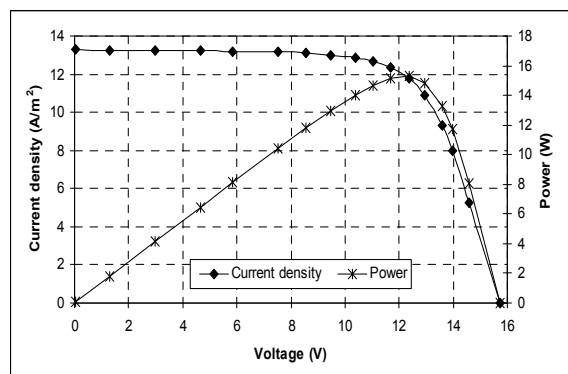


Figure 4: Current voltage characteristics of PV module at 25°C and 800W/m² without the Fresnel concentrator.

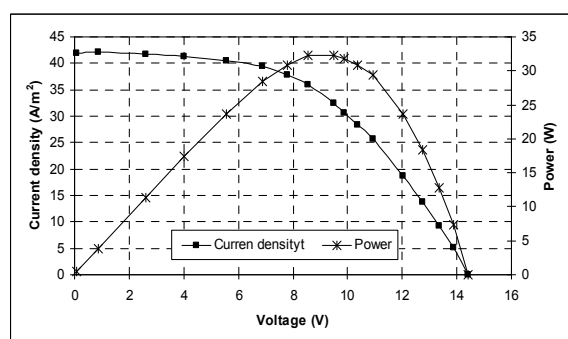


Figure 5: Current voltage characteristics of PV module at 55°C and concentration of 2.5 suns.

The measurement temperature was 55°C under concentration of 2.5 suns. The fill factor of the PV module due to concentration and higher operating temperature was deteriorated as evident from the shape of the I-V curve (figure 4). The efficiency and fill factor were 14.3% and 0.50 respectively. The power, current and voltage at the maximum power point concentration were 32.2W, 3.8A and 8.6V.

3.4. Electrical Outputs of two Systems without Concentrating Non-imaging Linear Fresnel Lens

An experiment was conducted on December 15, 2005 between 11:00am to 2:00 pm in order to ensure that the electrical output powers of both the PV modules were identical. Both the PV modules were fixed at an angle of 52° (Latitude + 15°) facing toward south. The variation of electrical power as a function of total global solar irradiance in the plane of PV modules is shown in figure 6.

The sky was not clear and sun was obstructed by clouds at number of occasions. The maximum total radiation in the plane of the PV modules was 550W/m². The two systems were installed very close to each other so that the all the parameters effecting the output were same during the measurements. The electrical output of the module (denoted as PV-2 in figure 6) which was used with non-imaging linear Fresnel lens was 0.2W higher than the module (denoted as PV-1 in figure 6) that will be used without concentrating lens. These measurements will allow normalizing the two outputs for comparative analysis after the linear Fresnel lens is installed on one of the PV modules.

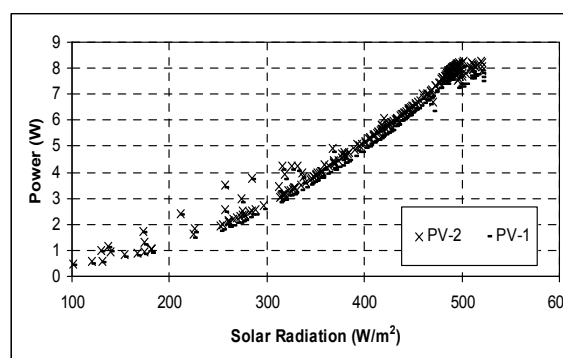


Figure 6: Variation of output power of the two PV modules at a fixed tilt angle of 52° as a function of incident solar radiation.

3.5. Available Solar Radiation

Concentrating Fresnel lens can concentrate only the direct radiation and hence the electrical output of the PV module under concentration depends on the availability of the direct radiation during the day. The presence of clouds, fog or other

environmental polluting species in the atmosphere will reduce the available direct radiation and, hence, the output of the PV module. The hourly averaged direct beam radiation normal to the plane of the PV module along with the total global and diffused solar radiation on horizontal surface on December 26, 2005 are shown in figure 7.

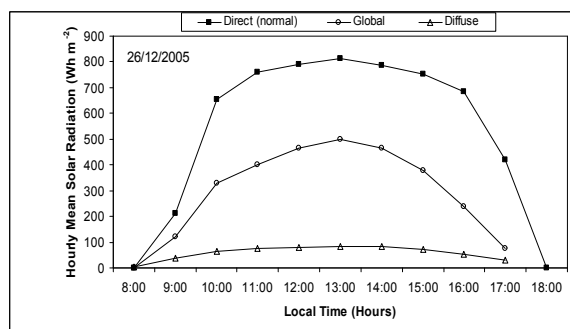


Figure 7: The hourly mean global, diffuse and direct radiation on horizontal surface of PV module on December 26, 2005.

The hourly mean direct radiation in the plane of PV module varied from 750 to 800 Whm⁻² whereas the hourly mean diffused radiation on the horizontal surface was less than 100 Whm⁻² during the measurement period from 11:00 to 14:00 hours. Figure 8 shows the averaged solar radiation on January 23, 2006.

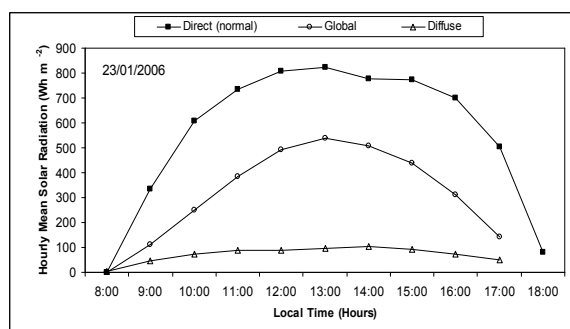


Figure 8: The hourly mean global and diffuse solar radiation on horizontal surface and hourly mean direct radiation normal to surface of PV module on January 23, 2006.

It was also a clear day except few small clouds appeared on the sky around 14:00 hours which reduced the direct radiation level with small increase in the diffused

radiation component. The hourly averaged direct beam radiation level was again between 700 and 800 Whm⁻² during the measurement duration.

3.6. Electrical Outputs of Concentrator PV and Non-concentrating PV Systems

Two experiments were carried out at two different clear sky days in Daejeon, South Korea. The first experiment was carried out on December 26, 2005 (see figure 7). The electrical power outputs of PV module with and without a non-imaging linear Fresnel lens from 11:00 to 14:00 hours are shown in figure 9.

The PV module without the concentrating Fresnel lens was fixed at an inclination angle of 52° facing towards the south whereas the PV module with concentrator was manually moved every 15 minutes so that it was facing towards the sun. The temperature variations of the two modules along with the ambient temperature during the measurement duration are shown in figure 10.

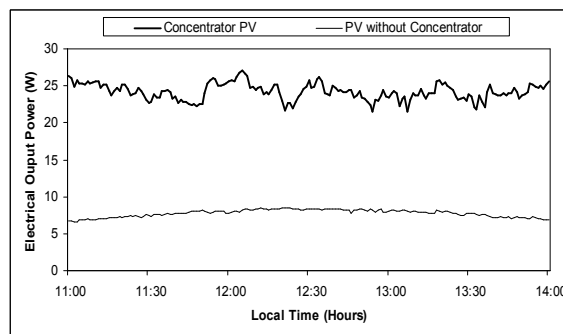


Figure 9: Variation of electrical power outputs of PV module with and without concentrator during the clear sky day of December 26, 2005.

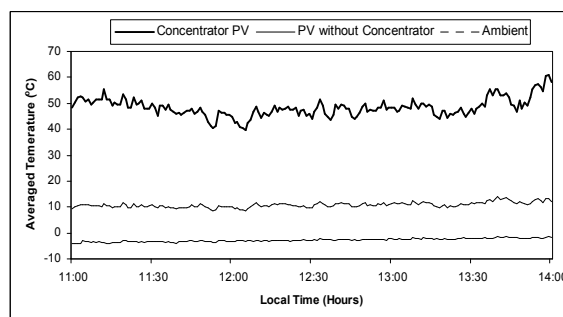


Figure 10: The variation of the temperature of PV modules with and without concentrator along with the ambient temperature on December 26, 2005.

The ambient temperature was below zero degrees Celsius during the entire length of measurements. The average temperature of the PV module without concentrating lens was 10°C. The temperature of PV module under concentration fluctuated between 40 to 60°C during the measurement time. The fluctuation in the temperature of concentrator PV module is due to varying wind speeds. Furthermore, the position of the concentrator was changed after 15 minutes and during that interval the concentrator was not always directly facing towards the sun which caused the variation in the solar radiation received at the PV module, and hence caused temperature fluctuations. The electrical power of PV module under concentration is approximately 4 times higher than that without Fresnel lens during the measurement duration.

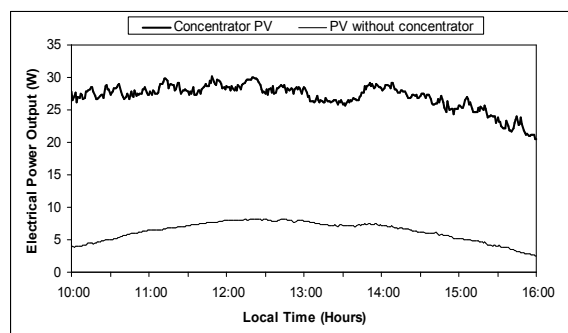


Figure 11: Variation of electrical power output of PV module with and without concentrator during the clear sky day of January 23, 2006.

It was also a clear sky day when the experiment was started, however, later during the day around 14:00 hours, a few clouds appeared on the sky reducing the direct radiation level (see figure 8). The maximum electrical power of the PV module without concentrator was 8W at 12:30 whereas it was 30W for PV module

with concentrator. Reduction in the electrical power was observed in both cases once the clouds started to appear on the sky. The variation in the operating temperatures of the both PV modules along with the ambient temperature is shown in figure 12.

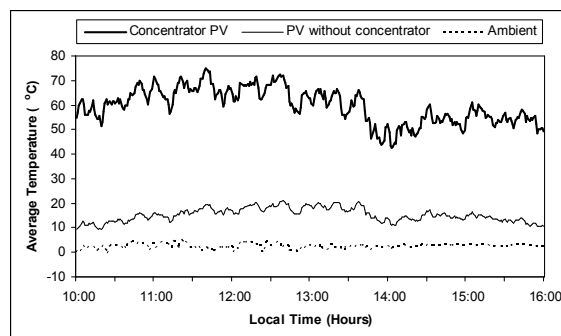


Figure 12: The variation of the temperatures of PV modules with and without concentrator along with the ambient temperature on January 23, 2006.

The temperature of PV module under concentration was as high as 75°C. The ambient temperature was 1°C. The temperature dropped from 68 to 43°C 13:30 due to reduced level of solar irradiance, therefore, there was no improvement in the electrical power output of PV module under concentration although the temperature was reduced. The electrical power of PV module under concentration is approximately 4 times higher than that without Fresnel lens. The effective concentration ratio was 3.2 but the increase in the electrical output was 4 times higher due to the fact that concentrator PV was tracking the sun whereas the other PV module was fixed. Both the outputs do not represent the output at the maximum power point but across a fixed load resistance.

4. CONCLUSION

A low concentrating photovoltaic system using a non-imaging linear Fresnel lens is designed and developed. The geometric concentration ratio of the system was 5.7. The optical efficiency of the concentrator

was 57% at an effective concentration ratio of 3.2. The optical efficiency and effective concentration ratio were lower than the expected values as effective width of the PV module was only 57% of the total concentrator aperture at PV module. The lateral distribution of temperature in the PV module showed that the temperature at the centre of the module was lower than the two ends (figure 3). The variation between the temperatures at different locations could be due to the non-uniform distribution of sunlight under the non-imaging linear Fresnel lens possibly arising due to nonalignment of the concentrating system as well as the variation in the Fresnel lens shape along its length. Outdoor current and voltage measurements showed that efficiency reduced from 21.8% to 14.4% under the concentration and resulting higher operating temperatures. The shape of the current-voltage curve was distorted and fill factor was 0.51 under Fresnel lens concentrator (figure 5) as compared to 0.70 without concentrator (figure 4). The electrical power output of the PV module with Fresnel lens was 4 times higher than the fixed PV module without the Fresnel lens on December 26, 2005 and January 23, 2006 during the measurement duration at Daejeon, South Korea (figures 9 and 11). The experience gained from the experiments on non-imaging linear Fresnel lens concentrator PV will be used as a first step towards improving the system performance and developing a large non-imaging linear Fresnel lens concentrating PV system in Korea.

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