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Characterizing the Declining CO_2 Emissions from Turkish Geothermal Power Plants

Serhat AKIN[1], Yasemin ORUCU[2] and Thrainn FRIDRIKSSON[2]

[1]Middle East Technical University, Ankara Turkey

[2]World Bank

[1]serhat@metu.edu.tr

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ABSTRACT

Turkish geothermal fluids have substantially higher carbon dioxide content due to the unusual geologic setting of the geothermal fields in the country. Typical emission factors at power plant commissioning range from 1,000 to 1,300 g/kWh that is almost 10 times higher than the global average emission factor for geothermal projects of 121 g/kWh. Despite unusually high initial CO_2 emission factors most, if not all, Turkish geothermal power plants have experienced gradual decline of CO_2 emission with time based on available data. Declining CO_2 emissions from 13 Turkish geothermal power plants located at Büyük Menderes and Gediz Graben are systematically investigated using geothermal power plant and well data. The average emission of these GPPs is 595.92 CO_2/kWh respectively, which is significantly lower than 2015 average (887 g/kWh). Simple predictive models based on decline curve analysis (DCA) of the CO_2 emission data collected from several geothermal power plant developers that allow prediction of $CO_2$2 emissions from geothermal power plants over the project lifetime are developed. The DCA method provides a good fit of the CO_2 emission data for geothermal power plants and the CO_2 production data for individual wells. Using DCA models future CO_2 production rates of wells and geothermal power plant emissions located were estimated. It has been observed that the declining CO_2 content of the fluid is linked to degassed brine that is reinjected into the reservoirs; however, due to lack of chemical and tracer test data it is not possible to confirm such hydraulic connections except for some fields. The rate of the decline is different between different power plants depending on the size of the geothermal field and the degree of hydraulic connection between injectors and producers. The emission decline rate of power plants changes from 5.59% to 9.99% per year.

1. INTRODUCTION

Geothermal energy is generally considered a relatively clean energy source with respect to release of the greenhouse gases to the atmosphere during power production. However, geothermal power plants emit carbon dioxide (CO_2), which is the most abundant greenhouse gas and contributes to global warming, and hydrogen sulfide (H_2S), which has a local effect due to its corrosive nature, odor, and toxicity in high concentration. Bertani and Thain (2002) reported CO_2 emission data from 85 geothermal power plants that ranged from 4 g/kWh to 740 g/kWh with the weighted average being 122 g/kWh. Even though it has been shown to be considerably less than from fossil fuel power plants in several locations such as Iceland (Armannsson, 2016, Armannsson et al., 2005) CO_2 emissions in Turkish geothermal power plants challenge those observed in coal and natural gas power plants (Fridriksson et al., 2016). Data provided by Akın (2017a), Herrera Martinez et al. (2016), Aksoy et al. (2015) and Haizlip et al. (2013) showed that emission factors obtained from geothermal power plants located in the Buyuk Menderes Graben range from 400 g/kWh to 1,300 g/kWh. Akın (2017a) and Herrera Martinez et al. (2016) reported similar CO_2 emissions from geothermal power plants located in Gediz Graben. Herrera Martinez et al. (2016) reported a weighted average of CO_2 emission of 887 g/kWh obtained from 12 geothermal power plants as of 2015. Using a model, they predicted that the total emissions of geothermal plants in Turkey will reach to 5.9 $MtCO_2$ with a constant 3.5% decline by 2023 assuming that power production will remain at 634 MWe.

Despite the high initial CO_2 emission factors some Turkish geothermal power plants located in Buyuk Menderes Graben have experienced gradual decline of CO_2 emission with time based on available data (Herrera Martinez et al., 2016, Akın, 2017a). In this study, the declining CO_2 emissions from Turkish geothermal power plants located at Buyuk Menderes and Gediz grabens are systematically investigated. A simple predictive model based on analysis of the emission data collected from geothermal power plant developers that allows prediction of CO_2 emissions from geothermal power plants over the project lifetime with defined certainty limits is developed. Using this model predictions of emissions over the life time of the geothermal power projects is assessed.

2. ORIGIN OF CARBON DIOXIDE IN GEOTHERMAL FLUIDS OF WESTERN TURKEY

Concentrations of non-condensable gas in reservoir fluids of high enthalpy geothermal resources in western Turkey are typically between 1% to 4% by weight. In Kızıldere geothermal field, the average non-condensable gas (NCG) concentration in the deep reservoir (3%wt NCG) is approximately twice the shallow reservoir (1.5%wt NCG) (Haizlip et al., 2013). The southern part of the liquid dominated Alaşehir geothermal reservoir has 2% to 4% CO_2 by weight, which is slightly more than that of the Kızıldere reservoir. The high salinity Tuzla Geothermal System situated in north-western Turkey on the Biga Peninsula, which is located at the west end of the Northern Anatolian Fault system is an exception, with 0.5%wt CO_2 (Baba et al., 2004). The non-condensable gas consists of largely (>96%) CO_2 that is dissolved in the relatively high temperature (>200°C) liquid-dominated reservoirs. On the contrary, Bertani and Thain's collected data showed that the average CO_2 content in the geothermal non-condensable gas is 90.5%. High CO_2 emissions from geothermal power plants in Büyuk Menderes and Gediz grabens in western Turkey are a result of unusual geological settings. Carbonate-dominated metamorphic rocks of the Buyuk Menderes and Gediz grabens including marbles, dolomitic marbles and calcschists form reservoir rocks. The calcite in these rocks provides a large potential source of CO_2 when the calcite equilibrates with water at reservoir temperatures. The dissolution of calcite to calcium and carbonate, bicarbonate, or water and CO_2 is accelerated by acidic conditions, temperature and depressed by salt concentrations. Stable isotopes of water show that the source of geothermal fluids in western Turkey is local meteoric water. Carbon isotopes from geothermal CO_2 indicate that the CO_2 in geothermal fluids is from marine carbonate sediments (Haizlip and Haklıdir, 2011, Yıldırım and Güner, 2005, and Şimşek, 2003). There is no indication of magmatic CO_2 in the isotopes or in the geologic environment. The source of CO_2 observed in producing geothermal fields located in the aforementioned grabens is dominantly crustal carbonates. Quantitative assessment of the various contributions to the volatile inventory in western Anatolia conducted by Mutlu, et al. (2008) revealed that 70% to 97% of the total carbon budget is provided by crustal marine limestone followed by 1.04% to 26.6% sediments and between 0.03% and 4.37% mantle rocks. This conclusion is not surprising since the basement in most parts of western Anatolia is represented by metamorphics of the Menderes Massif, consisting of gneiss–schist–marble lithologies. Regrettably, little is known about the natural CO_2 emissions from geothermal systems in Turkey, via diffuse surface emission, steam vents and hot springs and as a result it is not possible to estimate the net effect on geothermal power production from these systems on CO_2 emissions to the atmosphere.

3. METHODOLOGY FOR ASSESSING DECLINE OF CO_2 EMISSIONS FROM TURKISH GEOTHERMAL POWER PLANTS

Despite the high initial CO_2 emission factors some Turkish geothermal power plants such as Gürmat's Galip Hoca geothermal power plant in Germencik have experienced gradual decline of CO_2 emission with time based on available data (Herrera Martinez et al., 2016). Similar decline was reported for wells operated in Kızıldere geothermal field (Herrera Martinez et al., 2016) and Alaşehir geothermal area in the Gediz Graben (Akın, 2017a). Although the rate of the decline is somewhat different between different fields, it is typically in the range of 10% per year to more than 50% per year in the most extreme cases. Since all produced non-condensable gases are released to atmosphere, the declining CO_2 content of the fluid is possibly linked to degassed brine that is reinjected into the reservoirs. Tracer tests and concentrations of conservative components such as Chloride can be used to confirm the hydraulic connection between injection and production wells. In Kızıldere and Germencik geothermal reservoirs hydraulic connectivity is confirmed with tracer tests as reported in Akın et al. (2016) and Akın and Gülgör (2018) respectively.

In order to model the decline of CO_2 concentration in geothermal fluids and to understand the relationship between this decline and production and reinjection measured data is required. The measured data includes

- Time series of production and injection rates for individual production and injection wells and cumulative production and reinjection rates for the reservoirs;

- Measured CO_2 concentration in total discharge from production wells;

- Total CO_2 emission rates measured from power plants;

- Chemical monitoring data showing return of reinjected brine to production wells, such as Chloride concentration of produced geothermal fluid and reinjected brine over time;

- Temperature and pressure data from observation wells to establish conditions in the reservoir;

- Well-head pressure data

- Data to quantify the volume of the reservoirs, e.g. aerial extent, thickness, porosity;

A data request via Geothermal Power Plant Investors Association (JESDER) has been send to geothermal power companies in June, 2019. Regretfully, only 11 companies positively responded to this data request. Data collected from these geothermal investors located in Büyük Menderes and Gediz Grabens consisted of flowmeter measurements as well as well pressure, temperature and chemical data from wells and geothermal power plants. The completeness of the data changed from field to field. Most wells and some geothermal power plants lacked CO_2/NCG measurement possibly due to financial reasons. In such cases, Dalton's Law – partial pressure method, which is presented in the following section has been used to calculate the CO_2 content. A total of 22 geothermal power plants with more than 100 production wells' data was used. Majority (17) of the geothermal power plants were binary ORC type whereas the remaining ones were flash power plants.

The data provided by developers are used to model declining CO_2 concentration in total discharge from production wells and geothermal power plant CO_2 emissions. The methodology involves the application of Decline Curve Analysis (DCA) to CO_2 production on well and field basis. This approach has been previously used and provided satisfactory results (Herrera Martinez et al, 2016). DCA is developed from empirical evidence in the oil and gas industry. In applying DCA to CO_2 produced from geothermal wells (fields) a harmonic process representing CO_2 production in a boundary-dominated flow is assumed. All production can be characterized as having an initial transient flow period followed by a boundary-dominated flow period. At early well life (within few months of production) decline is generally not noticed. During the transient period, since the degassed injectate has not reached production wells, CO_2 production is not accurately represented by decline curves. This is confirmed by checking Chloride concentrations as well as available tracer tests. Once reservoir production reaches stabilization, CO_2 decline follows Equation 1 provided that degassed brine that is reinjected into the reservoir reaches production wells. Here D_i is the decline rate (fractional change in rate per unit time) at CO_2 production rate q_i and b is an empirically determined exponent (sometimes called reservoir factor), and q is an independent CO_2 production rate variable. Harmonic decline takes place when b equals 1 with D_i approaching 0. Using this equation and an optimization method an equation representing CO_2 emission decline can be obtained for each well or geothermal power plant. This equation can then be used as a simple predictive model to predict future CO_2 production rate on well and power plant basis.

$$\frac{q}{q_i} = \frac{1}{(1 + b \cdot D_i \cdot t)^{\frac{1}{b}}} \tag{1}$$

This approach is verified using field data. The model that successfully describes the decline of each well and field is selected. Using the selected model, declining CO_2 content of the fluid can be assessed throughout the life time of the power projects.

3.1 NCG Measurements in Geothermal Fields

Most of the Turkish geothermal reservoirs are liquid dominated. As the geothermal water rises in the well, with the decrease of the pressure on the fluid, steam and the dissolved non-condensable gases (NCG), such as CO_2, pass into the gas phase. When the geothermal fluid reaches the surface, it consists of liquid water and steam consisting of water vapor and non-condensable gas. In order to determine the characteristics of each phase, separators and condensers at the well heads are used. The most common methods of measuring NCG and water vapor ratio in steam phase are gas bubbling and gas flowmeter methods. These measurements are based on similar methodology.

In gas bubbling method, the flow rate of NCG coming from the steam outlet of a mini separator is measured after passing through a condenser. As the water vapor condenses in the condenser, the NCG and the water (condensed steam) are separated. The condensed water accumulates in the gas washing bottle whereas NCG passes to a graduated cylinder. The volumetric flow rate of the NCG is determined by counting the bubbles passing in a given time interval. The amount of accumulated water in the gas washing bottle and the amount of NCG determined from graduated cylinder are proportionated to each other. This method is not accurate as it is may be affected by operator performance. Furthermore, it does not provide consistent results, especially in wells with slug flow type.

The logic behind gas flow metering method is similar to bubbling method but instead of counting bubbles, a gas flowmeter is used to measure the NCG flow rate. The common procedure is to measure the NCG flow rate and steam condensate accumulation rate separately by using a condenser, gas flowmeter and a steam sampling port, which is also used in the standard practice for gas sampling in two phase geothermal fluid flow (ASTM E1675 -95a). NCG flowmeters that operate based on heat transfer and first law of thermodynamics are used. The temperature difference between the two resistance temperature detectors is used to measure gas volumetric flow. Due to temperature changes, this method is very sensitive to seasonal temperature differences. Due to its temperature dependence, it is required to know the gas composition passing through the flowmeter. Thus, it may lead to inaccurate measurements from well to well because of changing gas composition. Once the gas concentration in the steam phase is calculated, it is simply corrected to the gas weight at reservoir conditions by using steam fraction at the wellhead. The assumptions are as follows: (1) at the sampling conditions the amount of dissolved gas in brine is negligible compared to the total gas amount, (2) almost all of the gas is composed of CO_2 and (3) CO_2 exists only in the steam phase.

$$X = \frac{n_{CO_2}}{n_{H_2O}} \tag{2}$$

$$SF = \frac{E_{\text{Casing}} - E_{Brine\ (L)}}{E_{Steam} - E_{Brine\ (L)}} \tag{3}$$

$$GW_{Reservoir} = X * SF * 2.44 \tag{4}$$

Here X denotes mole fraction, SF represents steam fraction. E_{casing}, $E_{Brine(L)}$ and $E_{Steam(v)}$ stands for enthalpy of liquid at the top of feeding zones, enthalpy of brine and steam phases at sampling condition respectively. Overall, gas wt/wt concentration at reservoir condition ($GW_{Reservoir}$) is the product of X and SF.

3.2 Gas Weight Measurement by Using Dalton's Ideal Gas Law – Partial Pressure Method

In the geothermal power projects that have individual separators on production well pad, brine and steam are separated and they flow through separate pipelines to the power plant. In such cases, it is easy to record pressure and temperature values of steam phase and brine separately. Thus, NCG-steam ratio of the well can be calculated continuously by using Dalton's Law, which is based on the partial pressure ratio and mole fraction relationship. Generally, instead of using an individual separator on well pad, sometimes a central gathering system that collects all of the produced fluid in a central separator. In such a gathering system, steam, NCG and brine flow simultaneously in the production line, which makes it difficult to achieve laminar flow conditions. In such gathering systems, by using Dalton's law – partial pressure method, only the average CO_2 weight fraction of the field can be obtained using data collected from steam line. Thus, Dalton's law – partial pressure method may lead to wrong interpretations for individual wells in gathering systems, but it gives reliable results for obtaining field average value at the separation station.

The Dalton's Law states that the total pressure exerted by a mixture of gases is equal to the sum of the partial pressures of the gases in the mixture. From the partial pressure of a certain gas and the total pressure of a certain mixture, the mole ratio of gases can be found. The mole ratio describes the weight fraction of the mixture is a specific gas. The gas composition is required to calculate the partial pressure of each gas.

In a geothermal steam line, the total exerted pressure is the summation of saturated steam pressure and NCG partial pressure. The total gas pressure is measured with a proper pressure transducer in production line. Saturated steam pressure can be calculated from an empirical formula, which is given in Equation 5 (Martin Marietta Energy Systems, 1993). Steam does not behave as an ideal gas at high temperature and pressure. Thus, it should be corrected by using real gas equations such as Peng and Robinson (1976) or Redlich and Kwong-Soave (1949). It was observed that gas weights found by using ideal gas and real gas equations showed similar results. For simplicity, ideal gas approach can be implemented. Partial pressure of NCG can be obtained simply by subtracting water pressure from the total exerted pressure. Thus, by using the relation of pressure ratio and mole fraction, NCG concentration can be found using equations 5 through 7. Since most Turkish geothermal waters consist of more than 98% CO_2 at reservoir conditions, NCG is assumed as pure CO_2 in the calculations.

$$P_{H_2O(v)} = \exp\left[\frac{A + CT + ET^2}{1 + BT + BT^2 + FT^3}\right] \tag{5}$$

Where;

A= -7.395489709, B= 4.884152x10^{-3}, C= 3.6337285x10^{-2}, D= 4.308960x10^{-6}, E= 2.651419x 10^{-5}, F= -4.14934x 10^{-9},

T= Temperature (°C), $P_{H2O(g)}$ = (Mpa)

$$P_{Total} = P_{CO_2} + P_{H_2O(g)} \tag{6}$$

$$\frac{P_{CO_2}}{P_{H_2O}} = \frac{n_{CO_2}}{n_{H_2O}} \tag{7}$$

Once, saturated steam pressure is calculated from Equation 5, partial pressure of CO_2 can be obtained by subtracting steam pressure from total gauge pressure. The remaining calculations are carried out as described in the previous section.

4. RESULTS AND DISCUSSIONS

Data collected from 11 different developers with 22 geothermal power plants (5 Flash, 17 Binary) was evaluated. Regretfully, CO_2 emissions were measured only in 14 GPPs (installed capacity of 547.2 MW) corresponding to 25.92% of total geothermal power plants (54) in Turkey. The data collected from 8 binary (194.8 Mw) and 6 flash (352.4 MW) GPP's corresponds to %36.16 of installed geothermal capacity in Turkey. The total working capacity of these GPP's is 385.1 MW obtained from 100 producing wells. Initial and current (as of the end of 2019) average CO_2 production rates of these GPP's are 37.32 and 18.74 ton/hr respectively. Power weighted average of initial and current CO_2 production rates are somewhat higher, 54.07 and 24.81 ton/hr respectively (Table 1). As a result, power weighted average and arithmetic average CO_2 emissions of these GPP's are 582.16 and 595.92 g CO_2/kWh, which are significantly lower than previously reported arithmetic average of 887 g CO_2/kWh (Herrera Martinez et al, 2016).

Table 1. Initial and August 2019 emissions (ton/hr) of geothermal power plants.

GPP	Graben	Date	Installed Capacity	Initial CO_2 rate, ton/hr	August 2019 rate, ton/hr	% Decline/year
K-1	Büyük Menderes	2017	18	18.99	6.29	100.95
K-1 K-2 K-3 U1 K-3 U2	Büyük Menderes	1984	260	15.69 (2012) 72.93 (2013) 149.01 (2017) 56.16 (2018)	1.82 16.79 60.7 52.69	14.25 34.71 72.74 6.59
S-1	Gediz	2018	14.5	14.93	3.77	296.02
T-1	Gediz	2014	24	12.25	4.32	36.71
T-2	Gediz	2016	24	22.47	8.95	50.356
T-3	Gediz	2018	30	27.53	17.98	53.11
A-1	Gediz	2015	45	-	-	-
M-1	Gediz	2018	12.3	22.24	12.02	85.02
M-3	Gediz	2019	48	30	20.78	44.37
B-1	Büyük Menderes	2016	24	22.8	0.19	3966

G-1	Büyük Menderes	2009	47.4	46.13	-	-
Power	**Weighted**	**Average**		49.07	24.81	225.62
Arithmetic	**Average**			36.59	17.19	396.79

Simple predictive models based on decline curve analysis (DCA) of the CO_2 emission data collected from several geothermal power plant developers that allow prediction of CO_2 emissions from geothermal power plants over the project lifetime with defined certainty limits are developed (Table 2). Two sample DCA models from Gediz and Büyük Menderes grabens are presented in Figure 1. Binary GPP's CO_2 emission was calculated using aforementioned Dalton's law – partial pressure method. A rapid decline (85.02%) is observed right after commissioning of the binary GPP possibly due to favorable hydraulic connection between the injection and production wells. The CO_2 emissions given in the same figure are of two flash units located in Büyük Menderes graben. It can be seen that measured CO_2 emission of K-2 show a gradual decline (34.71%) significantly less than that of the binary GPP. The gradual decline can be attributed to less favorable hydraulic connection between injectors and producers. Another possibility for gradual decline is due to the size of the geothermal reservoir. In larger reservoirs where the pore volume is significantly large CO_2 emission decline rate will be less than that of a smaller reservoir.

Table 2. Emission (g CO_2/kWh) of geothermal power plants as of August 2019.

GPP	**Graben**	**Date**	**Installed Capacity**	**GPP Emission g CO_2/kWh as of August 2019**	**GPP Emission g CO_2/kWh as of August 2024**	**GPP Emission g CO_2/kWh as of August 2029**	**Decline/year 2019 - 2024**	**Decline/year 2019 - 2029**
K-1	Büyük Menderes	2017	18	792.03	168.79	97.8	16.37	8.95
K-1 K-2 K-3 U1 K-3 U2	Büyük Menderes	1984	260	692.91	108.25	14.57	16.88	9.79
S-1	Gediz	2018	14.5	267.82	163.17	119.54	7.81	5.54
T-1	Gediz	2014	24	218.90	60.95	13.97	14.43	9.36
T-2	Gediz	2016	24	453.76	60.68	9.4	17.33	9.79
T-3	Gediz	2018	30	898.00	284.41	107.43	13.67	8.80
A-1	Gediz	2015	45	155.582	45.84	13.16	14.11	9.15
M-1	Gediz	2018	12.3	1356	39.37	1.05	19.42	9.99
M-3	Gediz	2019	48	1105	183.64	46.15	16.68	9.58
B-1	Büyük Menderes	2016	24	19.15	-	-	-	-
G-1	Büyük Menderes	2009	47.4	425	-	-	-	-
			Power Weighted Average	582.16	103.00	25.38	13.97	8.23
			Average	595.92	111.51	42.31	15.19	9.00

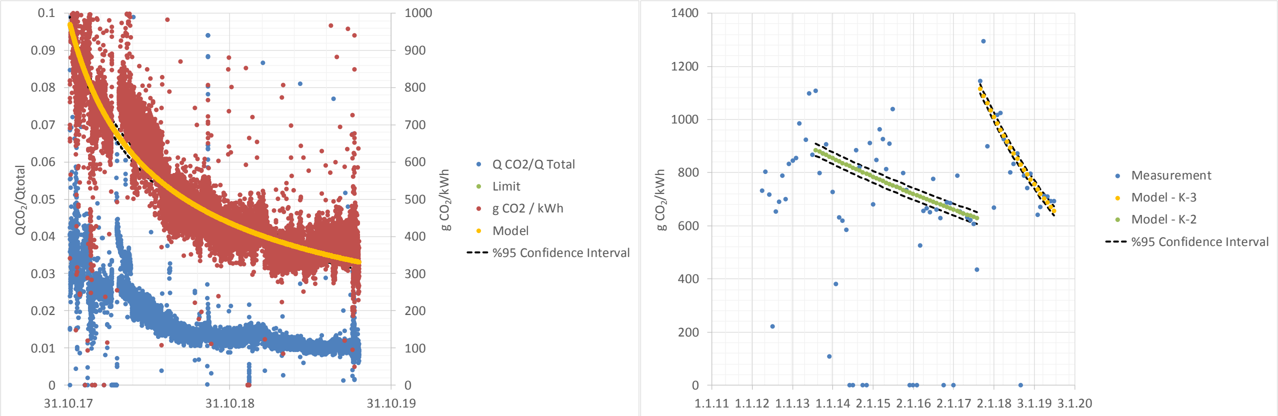

Figure 1. GPP CO_2 emissions. Left: single unit binary GPP in Gediz graben. Right: Flash GPP's in Büyük Menderes graben.

Using these models power weighted average emissions in 2024 and 2029 are predicted as 103.0 and 25.38 g CO_2/kWh assuming that current production levels are attained. Arithmetic average emissions at the same period are estimated to be 111.51 and 42.31 g CO_2/kWh respectively. It has been observed that carbon dioxide emission rates from all of these actively operating geothermal projects in Turkey declined over time (Table 1 and 2) possibly due to a variety of mechanisms.

1. Reinjection of the residual flashed brine with very low or zero gas content along with excess steam condensate back into the reservoir may dilute gas concentrations in the reservoir fluids. This requires an established hydraulic connection between injectors and producers that can be proven by tracer tests. For example, tracer test conducted in Alaşehir geothermal field showed a strong hydraulic connection between certain injectors and producers. Due to this strong connection the emission decline rate of A-1 is 61.44% between commissioning and 2019. On the other hand, for the same reservoir, relatively small but established hydraulic connections resulted in emission decline rate per year that changed from 35.31% to 33.86%. On the other hand, when there is no reinjection the emissions do not change. In Kızıldere reservoir a large portion (88.5%) of the Kızıldere power plant used water that was released to Büyük Menderes River by a 1.8 km channel between 1984 and 2002. During this time period, the produced CO_2 from the geothermal brine did not change.
2. Invasion of cooler, less gaseous peripheral waters into the reservoir in response to production-induced drawdown may also occur and reduce reservoir gas concentrations. An example of this can be K-1 GPP located in Büyük Menderes graben where tracer tests showed that there is limited hydraulic connection between injectors and producers. The emission's decline rate is 16.37% per year, which is somewhat larger than those located in Gediz graben.
3. Yet another reason for declining emissions is that, if the rate of CO_2 emissions due to power plant operations exceeds the natural rate of recharge of gas into the subsurface reservoir, the reservoir gas levels may decrease over time. It can be argued that this case is possibly responsible for most cases as the working - installed capacity ratios are somewhat small for most GPPs.

It should also be noted that the size of the geothermal reservoir is an important factor affecting CO_2 emission decline. For small reservoirs such as the K-1 and S-1 emission decline rates are 8.95% and 5.54% per year respectively. On the contrary, larger reservoirs such as Alaşehir and Kızıldere decline rates are smaller from 9.15% to 9.79% per year respectively. A similar observation is also valid for GPP size and CO_2 production rate (Table 1 and Figure 2). As the size of the GPP increases the CO_2 production rate increases exponentially. Since most of these GPP's are flash power plants it can be stated that flash GPP's have larger emissions compared to that of binary GPP's. An analysis was conducted to see the effect of geothermal area size and the number of producing wells on the emission declines. Figure 3 shows that as the working power capacity – area drained by producing well ratio increases the decline rate decreases, showing that drainage area of wells affects the CO_2 emissions.

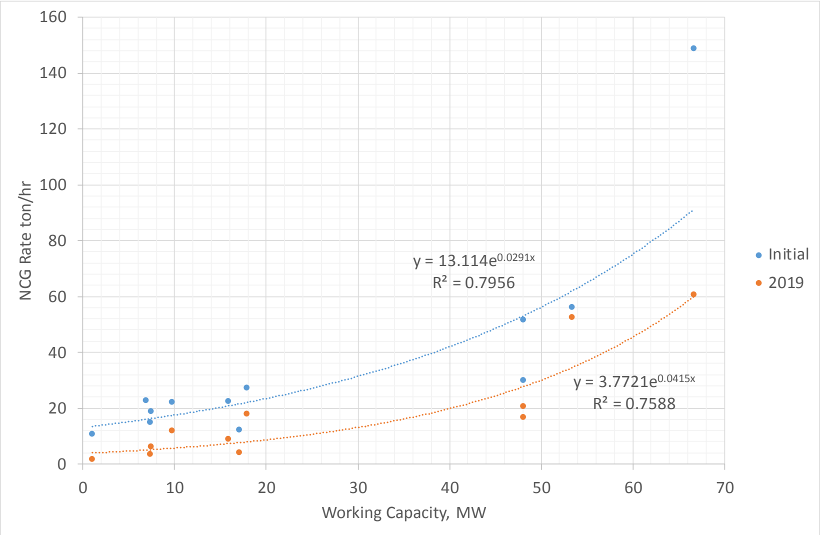

Figure 2. GPP working capacity - CO_2 emission (g CO_2/kWh) plot.

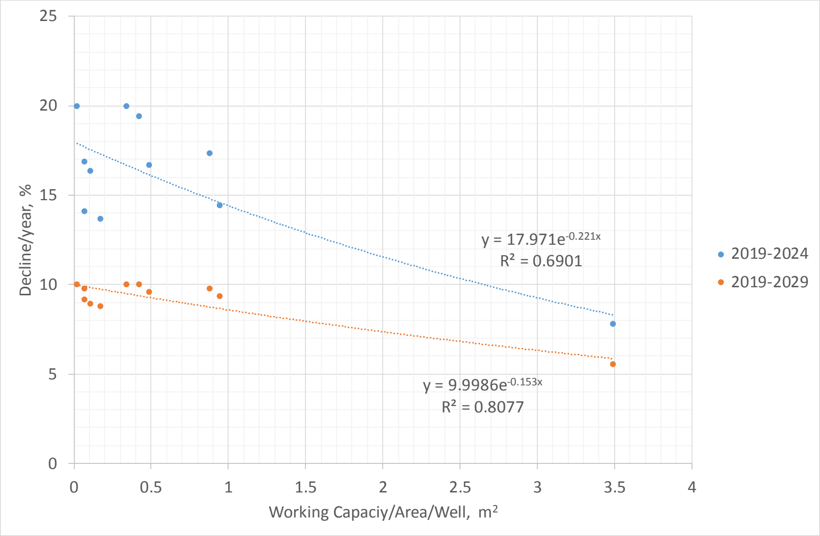

Figure 3. GPP working capacity / Area / Well - CO_2 emission (g CO_2/kWh) decline (%) plot.

CONCLUSIONS

Declining CO_2 emissions from Turkish geothermal power plants located at Buyuk Menderes and Gediz Graben are systematically investigated using geothermal power plant and well data. Simple predictive models based on decline curve analysis (DCA) of the CO_2 emission data collected from several geothermal power plant developers that allow prediction of CO_2 emissions from geothermal power plants over the project lifetime with defined certainty limits are developed. The DCA method provides a good fit the CO_2 emission data for plants and the CO_2 production data for individual wells. Using DCA models future CO_2 production rates of wells and geothermal power plant emissions located at Büyük Menderes and Gediz Graben can be estimated.

1. The initial CO_2 content in reservoir fluids at the beginning of production in Alaşehir and Salihli region are similar to those observed in Büyük Menderes Graben.
2. It has been observed that geothermal power plants feeding from wells that are located near or at the center of the graben have larger CO_2 concentration decline rates compared to those producing from near the horst section. In other words, deeper wells have larger CO_2 content in reservoir fluids compared to that of shallower wells. This observation has been validated for both Büyük Menderes and Gediz Grabens.
3. Some wells observe fast decline rates (more than 50%) possibly due to favorable hydraulic connection between injection and production wells. Due to lack of chemical and tracer test data it is not possible to confirm such hydraulic connections except for some fields.
4. The declining emissions change between 7.81% and 19.42% per year between 2019 and 2024. Power weighted average and arithmetic average decline of 14 GPPs are 13.97% and 15.19% per year respectively.
5. The range of decline in the CO_2 emissions in g/kWh for different power plants are given in Table 2. The arithmetic average and power weighted average of 14 GPP's CO_2 emission are 595.92 and 582.16 g CO_2/kWh respectively, which is significantly lower than 2015 average (887 g/kWh). Power weighted average emissions of GPP's in 2024 and 2029 are estimated to be 103 and 25.38 g CO_2/kWh respectively.

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