MATHEMATICAL MODELLING OF GEOTHERMAL CARBON DIOXIDE PRODUCTION IN A SPECIFIC GEOTHERMAL FIELD IN TURKEY

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MATHEMATICAL MODELLING OF GEOTHERMAL CARBON DIOXIDE PRODUCTION IN A SPECIFIC GEOTHERMAL FIELD IN TURKEY

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ABSTRACT

MATHEMATICAL MODELLING OF GEOTHERMAL CARBON DIOXIDE PRODUCTION IN A SPECIFIC GEOTHERMAL FIELD IN TURKEY

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Turkey’s non-condensable gases production from geothermal fields is very high when compared to other countries’ average production values. A big predominance of these gases is generally carbon dioxide (CO_2) and the origin of this CO_2 is generally meteoric for the studied area as reservoir rocks are carbonate-dominated metamorphic rocks such as dolomitic marbles and marbles.The dissolution of calcite mineral within the reservoir rocks, where it equilibrates with water, results in CO_2 release from the system. And this release occurs because of meteoric waters. When a field is put on production, a CO_2 decline is observed during the production life time and this decline can be addressed in three different scenarios. First, re-injected brine does not include any CO_2 as it is released to the atmosphere after production. When this brine reaches to the production wells due to the strong hydraulic connectivity, a sharp CO_2 decline occurs in the reservoir. Second, there might be a weak hydraulic connectivity between the production and re-injection wells and a gradual CO_2 decline may be observed with time due to the natural recharging. Last, a CO_2 decline may occur as a result of a sharp pressure decline in an excessively producing well because of the water invasion that comes from the upper part/shallow part of the geothermal system and this sub-surface water has less amount of dissolved CO_2 in it. This study aims to clarify modelling of

CO_2 declines for an Alaşehir geothermal field. It has been observed that CO_2 declines show the best matches with the hyperbolic decline method introduced by Arp's in 1945. In this study, the reasons of the observed declines in Alaşehir geothermal field showed that a strong hydraulic connectivity between the re-injection and production wells resulted in a sharp CO_2 decline. On the contrary, a gradual CO_2 decline has been observed when there is a weak hydraulic connectivity between the wells.

Keywords: Carbon Dioxide, Production Decline Curve Analysis, Non-condensable gases.

ÖZ

TÜRKİYE’DE JEOTERMAL BİR SAHANIN KARBONDİOKSİT ÜRETİMİNİN MATEMATİKSEL MODELLENMESİ

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Türkiye’deki jeotermal sahalardan üretilen yoğuşmayan gazların oranı diğer dünya ülkelerdekine kıyasla çok daha fazladır. Bu üretilen yoğuşmayan gazların büyük bir çoğunluğu ise karbondioksittir. Çalışma alanı içinde bulunan rezervuarımız, dolomitik mermer ve mermer gibi kayaçları barındıran karbonat ağırlıklı metamorfik kayaçlardan oluşmaktadır. Karbonat içerisinde bulunan kalsit mineralleri su ile dengeye geldiğinde ise çözünmekte ve CO_2 açığa çıkarmaktadır. Çalışılan bölge içindeki saha için bu açığa çıkan karbondioksitin kaynağı meteorik kaynak olarak belirtilmektedir. Bir jeotermal sahası üretime geçtiği andan itibaren, üretim süresi boyunca CO_2 azalımı gözlenmektedir ve bu CO_2 azalımı 3 farklı senaryo ile açıklanabilir. İlk olarak, kuyuya geri enjekte edilen su CO_2’ten ayrıştırılır ve bu CO_2 doğrudan atmosfere salınır. Geri enjekte edilen suyun CO_2 oranı sıfıra yakındır. Kuyular arası hidrolik bağlantının yüksek olması nedeniye enjekte edilen bu su üretim zonuna ulaştığında daha az CO_2 çözer ve CO_2 üretimi zamanla azalmış olur. İkinci olarak, üretim ve re-enjeksiyon kuyular arasındaki hidrolik bağlantı zayıftır ancak doğal beslenme ile rezervuara giren CO_2 zamanla azalmaktadır. Son olarak ise, yüksek üretim yapılan kuyularda basınç düşüşü çok fazladır ve bu yüksek basınç düşüşü sebebiyle CO_2 üretimi zaman içerisinde azalmaktadır. Bunun sebebi ise jeotermal sistemimize sığ yerlerden gelen ve içerisinde daha az çözünmüş karbondioksit içeren yeraltı sularıdır. Bu çalışma, Türkiye'den seçilmiş bir saha olan Alaşehir jeotermal sahasının karbondioksit azalımının modellenmesini açıklamayı amaçlamaktadır. Çalışma sonucunda elde edilen modellemelere göre en iyi çakışmayı Arp (1945) tarafından geliştirilen hiperbolik azalım metodu göstermektedir. Bu çalışmada gözlenen CO_2 azalımının nedenleri göstermiştir ki; kuyular arasında yüksek bir hidrolik bağlantı var ise keskin bir CO_2 azalımı gözlenmiştir. Bunun tam tersi olarak, hidrolik bağlantının az olduğu yerlerde ise, CO_2 azalımı kademeli olarak zaman içerisinde gerçekleşmiştir.

Anahtar Kelimeler: Karbondioksit, Üretim Azalımı Değerlendirmesi, Yoğuşmayan gazlar

To my beloved family

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LIST OF ABBREVIATIONS

ABBREVIATIONS

B: Artesian Binary

BP: Pumped Binary

CH_4: Methane

$CaCO_3$: Calcium Carbonate

CO_2: Carbon Dioxide

CHP Plant: Combined Heat and Power Plant

DFN Model: Discrete Fracture Network Model

EUR: Estimated Ultimate Recovery

GW: Gigawatt

GW_e: Gigawatt Electrical

H_2S: Hydrogen Sulfide

IPR: Inflow Performance Relationship

Km: Kilometer

KWh: Kilowatt Hour

m: Meter

Mt: Mountain

MTA: General Directorate of Mineral Research and Exploration

MW: Megawatt

MW_e: Megawatt Electrical

MWh: Megawatt Hour

NCG: Non-Condensable Gases

pH: Potential Hydrogen

TPAO: Turkish Petroleum Corporation

US Dollar: United States Dollar

Wt %: Weight Percentage

1F: Single Flash

2F: Dual Flash

LIST OF SYMBOLS

SYMBOLS

b: Constant for Arp's Decline Curve Equations

D_i: Initial Decline Rate

q: Current Production Rate

q_i: Initial Production Rate

t: Cumulative Time

CHAPTER 1

INTRODUCTION

Geothermal energy is a renewable, sustainable and green energy and it is expected to replace by fossil fuel energies in the near future due to its environmental friendliness and cost effectiveness to generate electricity. Kılıç, (2016) reported that this environmental friendly energy source can be also used in some industrial areas such as heating, farming, irrigation etc.. Additionally, General Directorate of Mineral Research and Exploration (MTA) reported that 90% of geothermal fields in Turkey can be classified as low and moderate temperature reservoirs. Therefore, those fields can be used directly for heating, thermal tourism, industrial areas and the remaining 10% can be used for electric power production. In the last decade Turkey has achieved a great momentum regarding investment in geothermal power plants. Turkey has been included in the 1 GW_e country club in 2017. The current total installed geothermal power capacity in Turkey is 1514.7 MW_e as shown in Figure 1.1. By 2023, it is planned to reach 2000 MW_e. The main drive mechanism of geothermal investments in Turkey is feed in tariff mechanism provided by the government. The special incentives give a guarantee of purchasing electricity at a cost of 10.5 cent US Dollar per kilowatt hour (KWh) for 10 years. This encouraged the private sector to invest in geothermal projects.

Turkey plays an important role in this industry and it is rich in geothermal energy sources. Therefore, it can be said that it is one of the most active countries in the world. There are many geothermal fields with different characteristic properties in Turkey. The major fields are located on the Menderes graben and Gediz graben in western Turkey. Medium to high geothermal fields have been discovered in these regions. Highest temperature well (280 ^{o}C) was recorded in Kavaklıdere Alaşehir region. In Kızıldere, temperatures as high as 248 ^{o}C were reported. The remaining fields are located in other parts of Turkey such as East Anatolia and central of Anatolia region with reservoir temperatures less than 150 °C. The first high enthalpy discovery was in 1968 in Kızıldere field in western Turkey. After that discovery, some additional geothermal fields such as Germencik, Simav and Salavatli suitable for energy production were discovered around eighties (Aksoy et al., 2010).

Haizlip et al., (2015) reported that Denizli-Kızıldere geothermal field was discovered in 1968 and the first commercial power plant was constructed in 1984 with a capacity of 17.4 MW_e. After privatization, another 80 MW_e capacity power plant was put into production in 2013. By the end of 2019, the total installed geothermal power capacity in Kızıldere reached to 340 MW_e. In addition, the field has been characterized by high amount of non-condensable gases with a content of $\mathrm{CO_2}$ between 96% and 99%. According to the unpublished recent reports the depths of wells drilled up to date are ranging from 370 m to 4500 m.

The Aydın-Germencik field is located in the Büyük Menderes Graben in western Anatolia and was discovered by MTA (General Directorate of Mineral Research and Exploration). Several wells drilled up to date from the depth of 285 m and 2398 m. The temperatures of the reservoir range from 203 °C to 232 °C (Simsek et al., 2000).

The Çanakkale-Tuzla geothermal field is located in northwest Anatolia and the first well was drilled in 1982. The temperature was recorded as 174 °C at a depth of 333-553 m and then the second well was drilled up to 1020 m yet the temperature was recorded 174 °C again (Gokcen et al., 2004).

Mertoğlu et al., (2019) reported that produced $\mathrm{CO_2}$ from the geothermal fields in Turkey is directly released to the atmosphere. However, there is a 50-70% decrease in the $\mathrm{CO_2}$ amount for the last 11 years and this decrease is still ongoing. This decrease in the $\mathrm{CO_2}$ can be explained in the following manner; reinjected water has very low amount of $\mathrm{CO_2}$, meteoric water $\mathrm{CO_2}$, content that is naturally recharged in the reservoir has lesser $\mathrm{CO_2}$ content and finally $\mathrm{CO_2}$ decreases due to excessive fluid production decreasing reservoir pressure and thus the $\mathrm{CO_2}$ content.

Since all of the geothermal power plant are located in Western Turkey. It is worth mentioninig common reservoir properties. The reservoir fluid is liquid dominated, and most of them are of meteoric origin. The reservoir fluid includes non-condensable gases (NCG) up to 4 % in some wells. High NCG content is measured at very initial period of production. However, it shows a sharp decline after a while during production in most of the fields. The main reason of the decline is possibly fast recirculation of injection fluid in the reservoir. Most of the reservoirs in Western Turkey produce from metamorphic rocks. These metamorphic rocks mainly consist of quartz, schist and marble.

One of the most important geothermal fields in Western Turkey (known as Alaşehir geothermal field) has been evaluated in this study due to its high enthalpy and CO_2 content. Akin et al., (2018) reported that Alaşehir reservoir is liquid dominated and has non-condensable gases in the reservoir and more than 96% of these gases is CO_2. The reservoir temperatures change between moderate to high (200 $^oC\pm$ 50 ^oC). Haizlip et al., (2016) stated that calcite in the reservoir rocks including but not limited to dolomitic marbles, marbles and calc-schitst provides high potentials for CO_2 when the calcite equilibrates with water.

In addition to the above, in this study, CO_2 decline in geothermal wells were analysed by using Arp's equations. The field has a high permeable reservoir with liquid dominated geothermal fluid, which includes significant amount of NCG at the beginning of the production. Akin (2017) stated that the southern part of the reservoir is liquid dominated with 2% to 4% CO_2 by weight. Because of strong hydraulic connectivity between injection and production wells, reasonable amount of decline has been observed within few months of production. There are several studies in the field area. Aydin and Akin, (2019) proposed that there is no compartmentalization in the reservoir based on DFN (Discrete Fracture Network Model) modelling study supported by tracer test, geochemical components and interference test results. Aydin et al., (2018) studied the effect of CO_2 decline on reservoir pressure drop and IPR performance of wells in the field. Currently, there are 7 license holders producing a total of 210 MW_e from the field. The proximity of the license areas and small well spacing resulted in pressure interference and a sharp CO_2 decline was observed. A sharp flow rate decline (more than 60%) occurred in some production wells, which are somewhat away from re-injection area that stabilized after a year of production. However, the wells that are relatively far from an injection area showed a gradual decline rather than a sharp decline.

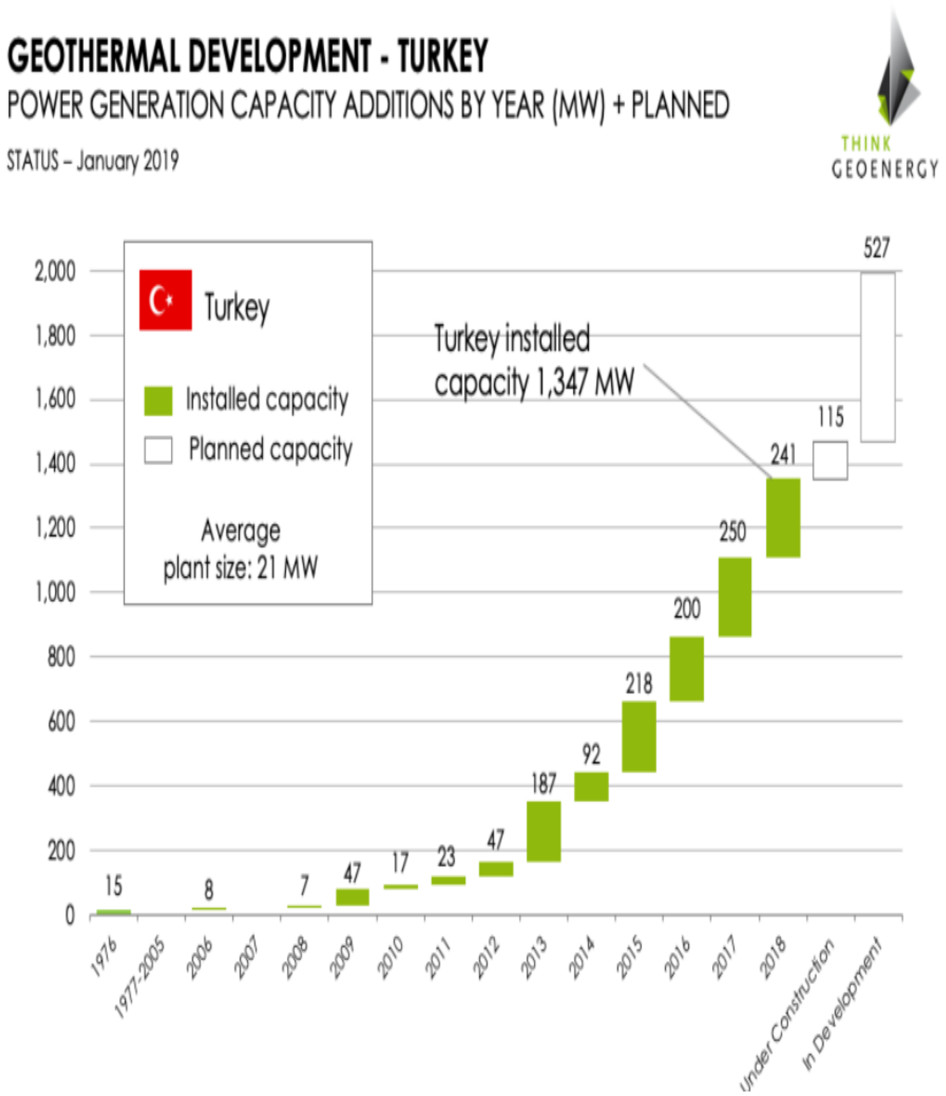

Figure 1.1 Power Generation Additions by Years (Web: ThinkGeoEnergy)

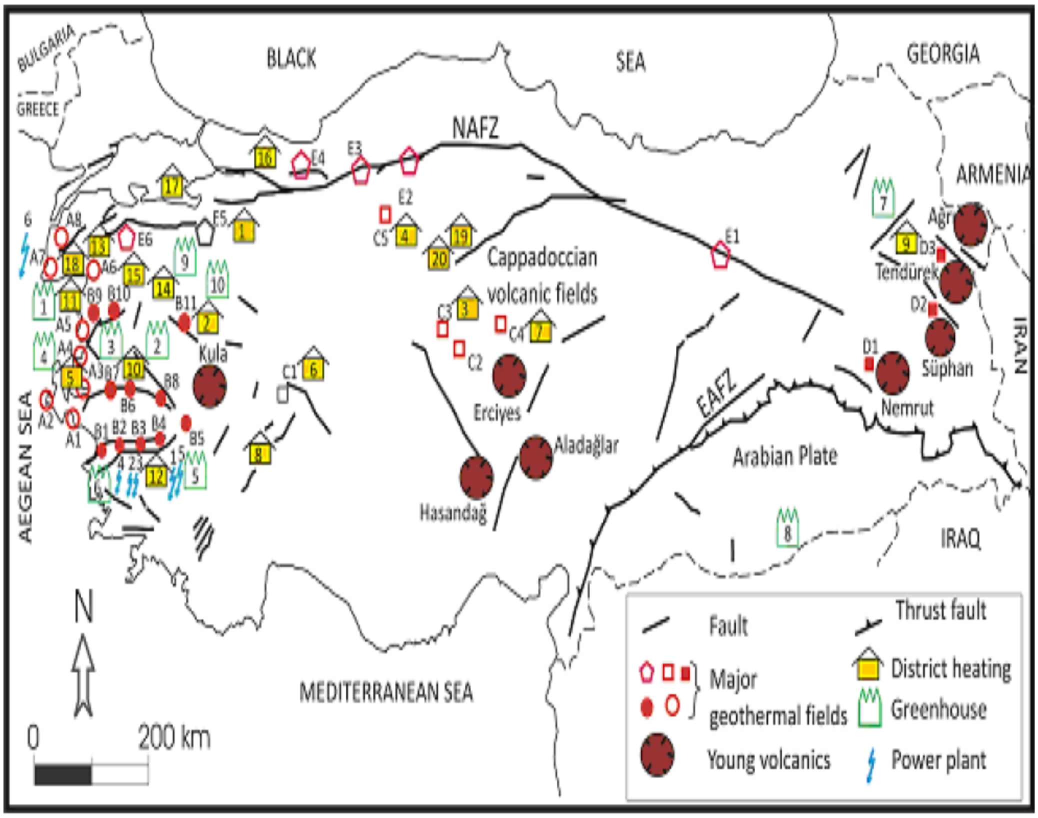

Figure 1.2 Location of Geothermal Fields in Turkey (updated from Serpen et al., 2009a)

CHAPTER 2

LITERATURE REVIEW

In this chapter, literature review studies have been conducted in order to obtain information regarding the origins of carbon dioxide of geothermal systems and their carbon dioxide emissions rates. Also, some specific searches have been carried out for the specific countries to make comparison between their geological characteristics and carbon dioxide emission amounts.

2.1 Origin of CO_2

Non-condensable gases (NCG) found in geothermal systems can be originated from different sources. Sedimentary, magmatic and meteoric water-rock interactions are among the main sources of naturally occurring NCG. Carbon dioxide constitutes the major component of NCG in geothermal reservoirs and origins of this carbon dioxide can be considered as follows:

- A small amount of the carbon dioxide can be derived from the geothermal fluid itself and this carbon dioxide is dissolved in sea water, meteoric water or recharging fluid as it enters to the relevant geothermal system. This small fraction of carbon dioxide can be considered insignificant when compared to the total dissolved carbon dioxide in geothermal fluids.
- A large amount of the carbon dioxide can be derived from host or bed rocks of the geothermal system. In volcanic geothermal systems, the dominant rock type is igneous rocks and these rocks contain little amount of carbonates. Because of the chemical interactions between the fluids

and rocks these carbonates can be released. Hence, in volcanic geothermal systems, the amount of carbon dioxide might be moderate if the major source of carbon dioxide is rock dissolution in geothermal fluid. Iceland geothermal fields (i.e Reykjanes, Nesjavallir) can be given as an example for this type of volcanic geothermal systems. Carbonate rocks may release large amount of carbon dioxide into the geothermal fluids as carbonates are major components in these systems. This large amount of carbon dioxide release can be occurred due to metamorphic processes or dissolution at high temperatures. These high temperature carbonate-hosted geothermal systems are not common around the world, yet western Turkey can be given as an example, and high carbon dioxide fluid concentration is observed in these geothermal systems. Sedimentary rocks also may contain a changeable amount of carbonates that results in carbon dioxide concentrations in the fluids.

2.2 Worldwide CO_2 Emissions from Several Countries

Some of the information regarding the non-condensable gases from different geothermal fields are as follows:

2.2.1 CO_2 Emissions in Icelandic Geothermal Fields

In Iceland, geothermal systems can be classified as low to high-temperature and these low-temperature systems are generally from Quaternary and Tertiary formations where the high-temperature systems are located onan active volcanism and rifting areas. The main heat source is due to the magma intrusions. Hence, it can be said that these geothermal systems are mostly volcanic (Arnorsson et al., 2008) and the origin of the carbon dioxide is magmatic.

The CO_2 emissions have been monitored for Icelandic geothermal plants since seventies as shown in the Figure 2.1 and CO_2 emission increases for some of the plants presented in the below figure can be discussed as follows (Armannsson, 2017):

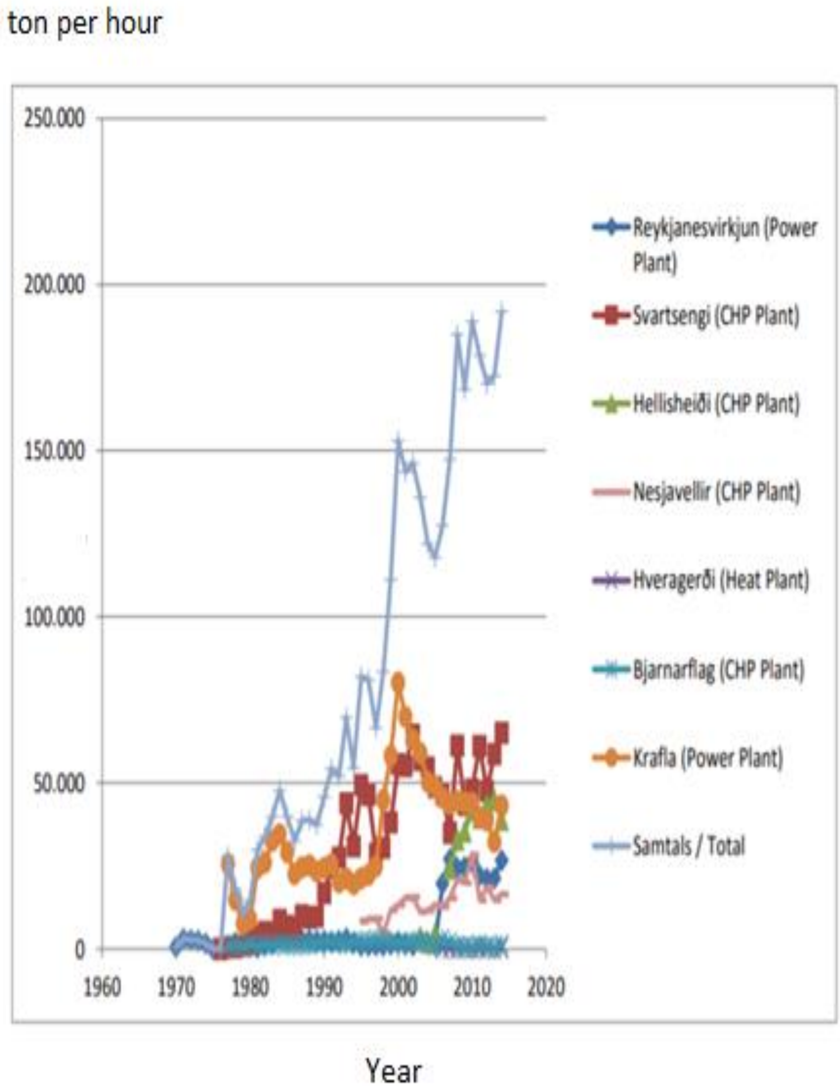

Figure 2.1 Gas Emissions from Geothermal Activity in Iceland 1970-2014 (Armannsson, 2017)

- Krafla (Power Plant): CO_2 emissions were slightly high during the eighties because of the magmatic gas. After that it has been stabilised yet another increase occurred around 2000 because of a production increase and since then a gradual decrease has been observed due to the steady production.

- Svartsengi (CHP Plant): CO_2 emission increased after nineties because of the formation of a steam cap and production from that steam cap.
- Hellisheiði (CHP Plant) and Reykjanesvirkjun (Power Plant): CO_2 emissions have increased during initial production in these geothermal power plants. However, the increase in Reykjanesvirkjun plant is not drastic compared to that in Hellisheiði plant.

Major geothermal power plants in Iceland can be divided into two groups according to the amount of CO_2 emissions per kWh. Krafla and Svartsengi can be classified as group one, and Reykjanesvirkjun, Hellisheiði and Nesjavellir can be classified as group two as shown in the Table 2.1. CO_2 emissions can be seen from the below table and it can also be seen that there is a significant decrease in group one since 2000 due to the cascaded use of heat and electricity.

Table 2.1 CO_2 Emissions per kWh from Major Geothermal Power Plants in Iceland (Armannsson, 2017)

Power plant	Electricity generation only		Heat and electricity production
	CO_2 ($gkWh^{-1}$) 2012	CO_2 ($gkWh^{-1}$) 2000	CO_2 ($gkWh^{-1}$) 2000
Krafla	100	152	
Svartsengi	150	181	74
Reykjanes	18		
Hellisheidi	19		
Nesjavellir	25	26	10

2.2.2 CO_2 Emissions in Geothermal Fields in Italy

Arias et al., (2010) stated that geothermal exploration started in the 19th century in Tuscany, Italy for the extraction of boric acid. Giovanni et al., (2005) reported that both Larderello and Mt. Amiata geothermal fields have so many similarities in terms of geological and geothermal aspects. In terms of geological similarities, the followings can be said; the shallow reservoirs are hosted in carbonate units and the deep reservoirs are hosted in the metamorphic formations. As for geothermal aspects it can be said that both geothermal systems can be classified as a high-temperature geothermal system for the deep exploration. The maximum observed temperatures are more than 400 °C at the depth of more than 3000 m for the both fields.

Bravi and Basosi, (2014) stated that in Mt. Amiata, non-condensable gases emissions are relatively high when compared to the world's average value. And these gases include but not limited to carbon dioxide, hydrogen sulfide and methane (CO_2, H_2S, CH_4). However, most of the emissions include CO_2 and the relevant CO_2 emission rates ranging from 245 kg/MWh to 779 kg/MWh with the average weighted of 497 kg/MWh.

The most reliable global survey on CO_2 emissions was presented by Bertani and Thain, (2002) and their survey included 85 power plants and 11 countries. It was found that CO_2 emissions from geothermal power generation ranged between 4 to 740g/kWh, with a power weighted average of 122g/kWh. The Figure 2.2 can give an idea about CO_2 emissions from different countries including Italy (Fridriksson et al., 2017):

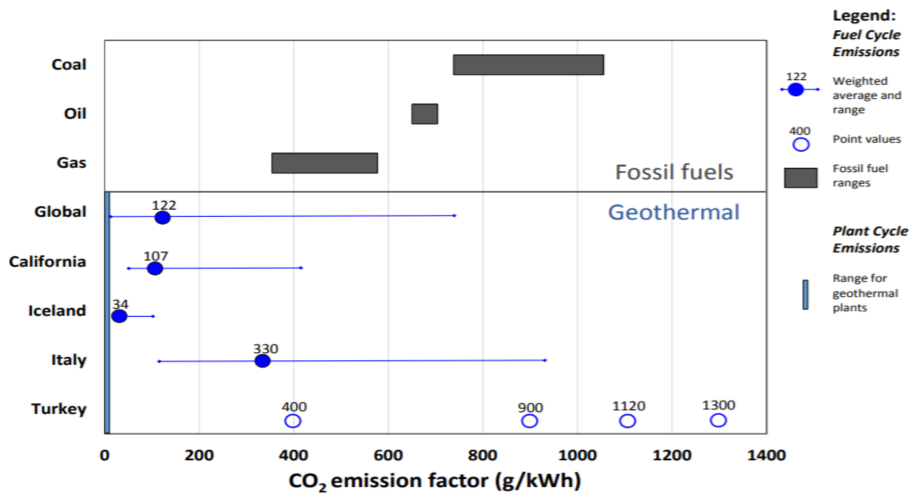

Figure 2.2 Weighted Average and Range of Emission Factors from Geothermal Power Plants (Fridriksson et al., 2017)

2.2.3 CO_2 Emission in Geothermal Fields in Turkey

In western Turkey, most of the explored geothermal systems have high non-condensable gas concentrations in reservoir fluids and these non-condensable gases contain 96-98% or higher amount of CO_2. Carbonate dominated reservoir rocks, which include dolomitic marbles provide a big potential source of CO_2 as the calcite mineral in these rocks equilibrates with water (Haizlip et al., 2016)

Akın et al., (2016) also stated that the source of CO_2 from the producing fields are due to the crustal carbonates found in the western Anatolia. Mutlu et al., (2008) reported that crustal marine limestones constitute total carbon budget from 70% to 97% which is followed by the sediments ranging 1.04% to 26.6% and mantle rocks from 0.03% to 4.37%. And this can be explained by the metamorphics of the Menderes Massif in the basement of the western Anatolia including gnessis-schist-marble lithologies.

The CO_2 emissions have been presented in Table 2.2. It can be seen that Turkey geothermal fields have high non-condensable gas contents ranging from 400g/kWh to 1120g/kWh for 2017:

Table 2.2 Turkey Geothermal CO_2 Emission Data (Layman, 2017)

Name of Power Plant / Project Site	Developer	Installed Capacity (MW)	Plant Tech-nology Type	Planned / Under Const. (MW)	Resource temp, deg C	CO2 in reservoir fluid, wt %	CO2 emissions rate, g/kwh	*Sources for CO2 data*
In Operation or Under Constructio n								
Kizildere	Zorlu	95	1F, 2F, B		200-245	1.9 - 4.4	900-1300	*Askoy et al (2015); Gokcen et al (2004)*
Kizildere	Bereket	6.9	B		140			*no data available*
Salavatli (Dora 1, 2, 3a)	Mederes Geothermal	50.9	B	37	171	1.0-2.2	900-1100	*Askoy et al (2015); Di Pippo (2012); Kaplan & Serpen (2010)*
Germencik	Gurmat	162.3	2F, B		230-276	1.5 - 2.1	813-1100	*Atkins International Ltd (2014); Askoy et al (2015); Tureyan et al (2016)*
Germencik	no data	22.5	F					*no data available*
Tuzla	Enda	7.5	B	7.5	174	0.5	400	*Askoy et al (2015)*
Hidirbeyli	Maren	92	B	96	180	1.5 - 2.0	1423	*Kaypakoglu et al (2015); Askoy et al (2015)*
Pamukoren	Celikler	45	B		161-191	1.54	925	*Karahan et al (2015); Askoy et al (2015)*
Alasehir	Turkeler	24	B		185	3.4	ND	*Askoy et al (2015)*
Alasehir-Kavaklidere	Zorlu	45	2F, B		287	3.4	1640	*ENVY (2013); Askoy et al (2015); Velzades & Associates (2012)*
Gumuskoy	BM	6.6	B	6.6	180	1.5 - 2.0	900-1100	*Askoy et al (2015)*
Yilmazkoy	KenKipas Energy	24	B?		175	2.0	ND	*Askoy et al (2015)*
Gerali-Sarakoy	Degirmenci / GreenEco Energy	24	B		124	ND	ND	*no data available*
Umurlu	Karadeniz Elektrik	12	B	12	155	ND	ND	*no data available*
TOTALS		617.7		147.1				
Planned Project								
Buharkent	Limak Yatirim	15	BP		146	0.2	0	*Mertogulu, Basarir & Saracoglu (2015)*

1F= single flash; 2F = dual f ash; B = artesian binary; BP = pumped binary

Also the difference between the CO_2 emissions of Turkey and Icelandic geothermal fields can be seen from the Figure 2.3 and it can be said that CO_2 emission is much more higher in geothermal fields in Turkey.

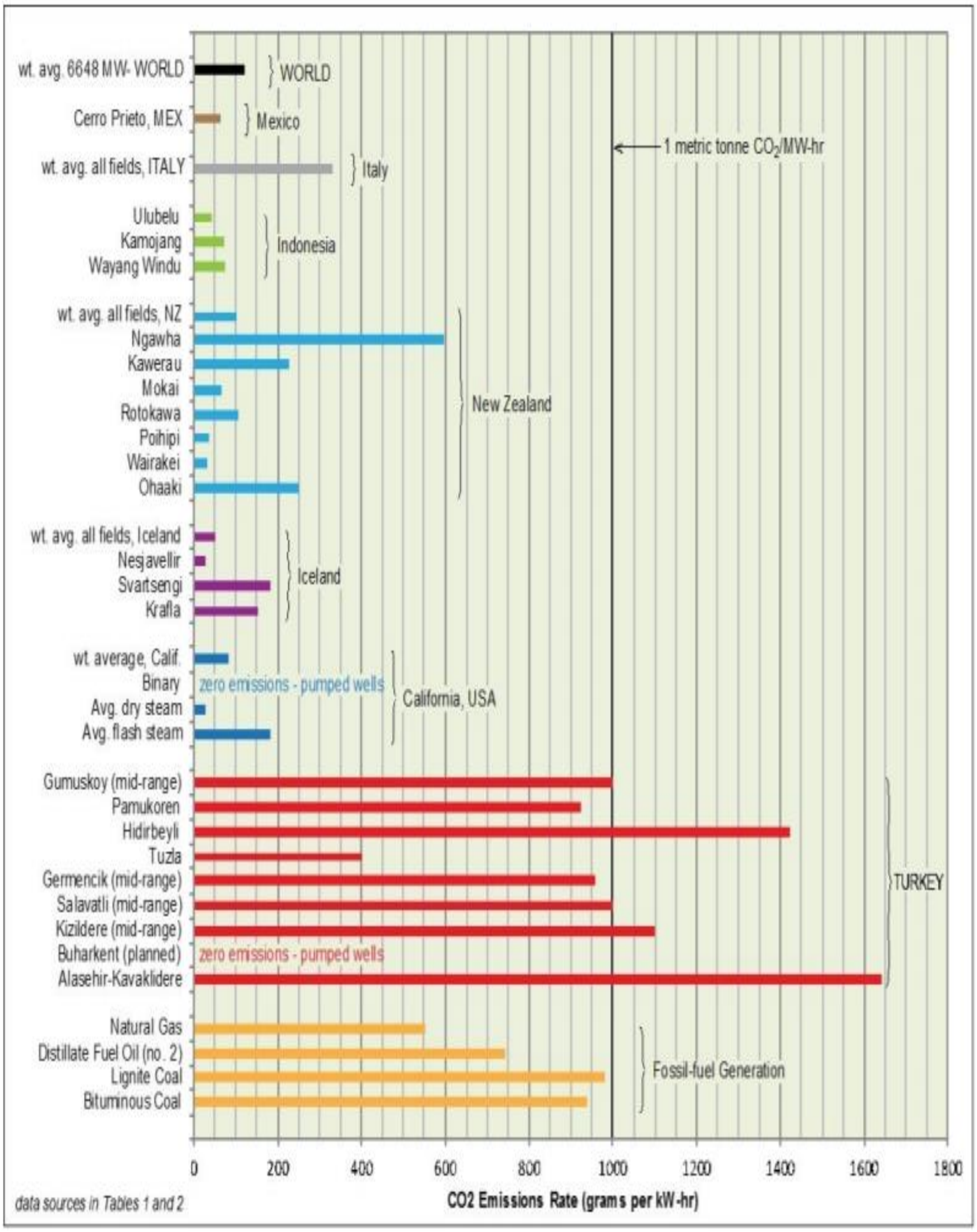

Figure 2.3 CO_2 Emission Rates for Turkey and Some Other Countries (Layman, 2017

In this study, wells located in one of the important geothermal fields in Turkey, Alaşehir geothermal field have been evaluated in order to predict future CO_2 emissions by using decline curve modeling.

CHAPTER 3

STATEMENT OF PROBLEM

Turkey's geothermal reservoirs include relatively higher NCG (non-condensable gases) compared to the world's average values. The majority content of non-condensable gases produced from Turkish geothermal reservoirs consists of mainly carbon dioxide (CO_2). In order to decrease emissions of these gases for environmental purposes some methods are being widely used. In this study, some of the selected wells from the Alaşehir geothermal field have been evaluated regarding the observed CO_2 declines by using a mathematical modelling method with the help of Arp's decline curve equations. The results proved that a CO_2 decline occurs continuously during the production lifetime of a geothermal reservoir. Additionally, modelling results showed that re-injection of produced brine from a well supports these declines. Further to that, a strong hydraulic connectivity between the re-injection and production wells plays a significant role in these CO_2 declines.

CHAPTER 4

METHODOLOGY

Decline curve analysis is a technique that uses production data from oil and gas fields. The aim of using this technique is to predict the future production forecast and to determine the estimated ultimate recovery (EUR) of the reserves.

J.J. Arps (1945) identified a relationship between the production rate and time considering the point where production has started to decline. Since that time, many papers have been published theoretically to interpret the Arps' decline equations. Yet, this still is the most widely used method for reservoirs' performance and reserve estimations.

Li and Horne (2003) reported that most of these techniques are based on empirical Arp's equations; exponential, hyperbolic and harmonic equations and the estimation of which equation will be used for the specific reservoir is case specific. One issue is that, each equation has its own advantages. For instance, the exponential equation estimation has tendency to underestimate reserves and production rates whereas the harmonic equation has tendency to overpredict the performance.

Exponential, hyperbolic and harmonic equations were introduced by Arps (1945). However, his work has been studied by others for some special cases. These studies are as follows:

- Fetkovich (1980), Fraim and Wattenbarger (1987) published type of curves to describe the decline curve analysis in hydrocarbon reservoirs;
- Li and Horne (2001) proposed an analytical method derived from the relationship between production rate and reciprocal of the total production; Reyes et al., (2004) applied this relation to the Geysers in order create another decline curve method.

Arp’s decline curve analysis is a very simple method and can be applied to any type of reservoirs. However, it can be said that subject method is limited regarding the two assumptions: the estimated ultimate recovery calculation should be carried out for unchanged production condition in the future and the decline condition presumes that a reservoir is at boundary dominated flow rate. Hence, this method shall not be used for the reservoirs where there is a transient flow. In addition to the above explanation, Arp’s decline curve equations have been frequently used to model oil production decline. For instance, Princewill et al., (2018) reported that this method has been used in Southeast Nigeria in order to carry out production forecast for a selected well for the year 2020 by using the production history starting from 1990. Brantson et al., (2018) stated that Arp’s decline curve equations have been applied to a specific well in the KN Field in Gulf of Guinea and production history of this well has been used to forecast the future production rate for a period of 20 years. Höök et al., (2010) confirmed that Arp’s equations have been used to evaluate future production amounts of the China’s 9 giant oil fields namely Changqing, Dagang, Daqing, Huabei, Liaohe, Shengli, Tarim, Xinjiang and Zhongyuan. The results showed that a considerable amount of oil decline from the abovementioned fields can be observed over the years as expected. In this study, CO_2 decline rates of some wells in a geothermal field have been obtained by using the same method while assuming wells are flowing in a boundary dominated manner.

The general Arp’s equation, which is used in a production well is given below and all the other equations that are used for production forecast are arranged by using this equation.

$$q_t = \frac{q_i}{(1+bD_i t)^{1/b}} \tag{1}$$

There are three (3) types of declines:

i. Exponential Decline; where b is equal to zero (0) and q is defined as a current production rate, q_i is initial production rate, D_i is initial decline rate and t is the cumulative time that passed from the start of the production. By using the above equation and considering b is equal to zero (0); exponential decline equation is arranged as:

$$\frac{q}{q_i} = \frac{1}{e^{D_i t}} \tag{2}$$

ii. Hyperbolic Decline; where b is between zero (0) and one (1) and q is defined as a current production rate, q_i is initial production rate, D_i is initial decline rate and t is the cumulative time that passed from the start of the production. Hyperbolic decline equation is given below:

$$\frac{q}{q_i} = \frac{q_i}{(1+bD_i t)^{1/b}} \tag{3}$$

iii. Harmonic Decline: where b is equal to one (1) and q is defined as a current production rate, q_i is initial production rate, D_i is initial decline rate and t is the cumulative time that passed from the start of the production. Harmonic decline equation is given below:

$$q = \frac{q_i}{(1-D_i t)} \tag{4}$$

Differences between harmonic, hyperbolic and exponential declines are shown in Figure 4.1 and as expected it can be said that hyperbolic declines occur between an exponential decline curve and a harmonic decline curve.

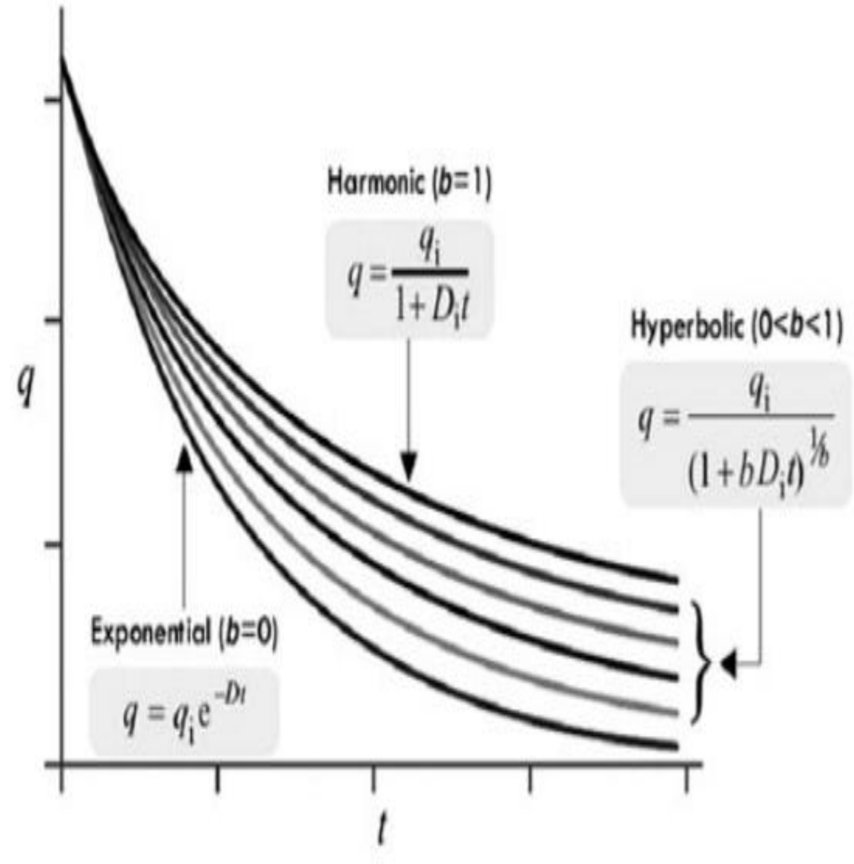

Figure 4.1 Comparison of Exponential, Hyperbolic, and Harmonic Relations (Shin et al., 2014)

CHAPTER 5

CHARACTERISTICS OF ALAŞEHİR GEOTHERMAL FIELD

Alaşehir geothermal field is one of the most imporant geothermal fields in Turkey and is located in Alaşehir Graben in West Anatolia. Dewey and Şengor (1979) reported that Alaşehir Graben (also known as Gediz Graben) is located 140 km east of Izmir and it is about 6-10 km wide for the subject study area and it expands along the Aegean Sea (Figure 5.1). The exploration activities have been started by TPAO (Turkish Petroleum Corporation) in 1989 and since then it has become more and more attractive for other companies and more than six different companies have drilled more than 100 wells up to date. Aydın et al., (2018) reported that there are six binary power plants and one combined flash-binary power plant that generate electricity from the relevant geothermal fields.

Çiftci and Bozkurt, (2009) identified stratigraphic units of the field as shown in Figure 5.2 and it is very clear from Figure 5.3 that Paleozoic metamorphites including marbles, micaschist and gneiss constitute the basement of Alaşehir geothermal field and there are marbles in the upper parts of the basement and these marbles are also called Azıtepe marbles, Karamanderesi at al., (1984). Yılmazer et al., (2010) stated that above these marbles there are Mesozoic ophiolithic rocks including but not limited to dolomites, limestones and sandstones. The sediments, which belong to Miocene and Pliocene cover the older units. Quaternary alluviums are located at the top of the lithology. Yılmaz et al., (2010) reported that the Gediz graben is an active tectonic region and due to this active tectonism there are several active faults in the Alaşehir graben as seen in Figure 5.4 given below.

A geological conceptual model of the Alaşehir geothermal field has been identified by Çiftci and Bozkurt, (2009) and this conceptual model is given in Figure 5.5. As per this subject model it can be said that geothermal fluid has a meteoric origin and there are many conductive faults within the geothermal system that create several paths between the surface and subsurface. The meteoric fluids and spring waters that come from the surface travel through these conductive faults and reach to the reservoir rock. Since meteoric water is acidic, calcite minerals are dissolved in marble and with the increasing temperature and pressure values with respect to depth, it turns into geothermal fluids (brine).

Akın (2017) reported that in the southern part of the Gediz graben, there are a number of deep wells where their depths change between 1100 m and 2500 m. Well depths can reach more than 3000 m in the center of the Gediz graben and in this part, at a depth of 3011 m, the highest observed bottom hole temperature is 251 ^{o}C.

Gürel (2016) also reported that the Alasehir geothermal field has a range of reservoir temperatures between 140 ^{o}C to 250 ^{o}C. He reported that the net and average gross reservoir thickness are 650 m and 1200 m respectively.

Akın (2017) stated this study area has good permeability-thickness from the fractures that are observed in the graben and the subject reservoir fluid is liquid dominated with more than 2% of non-condensable gases including CO_2.

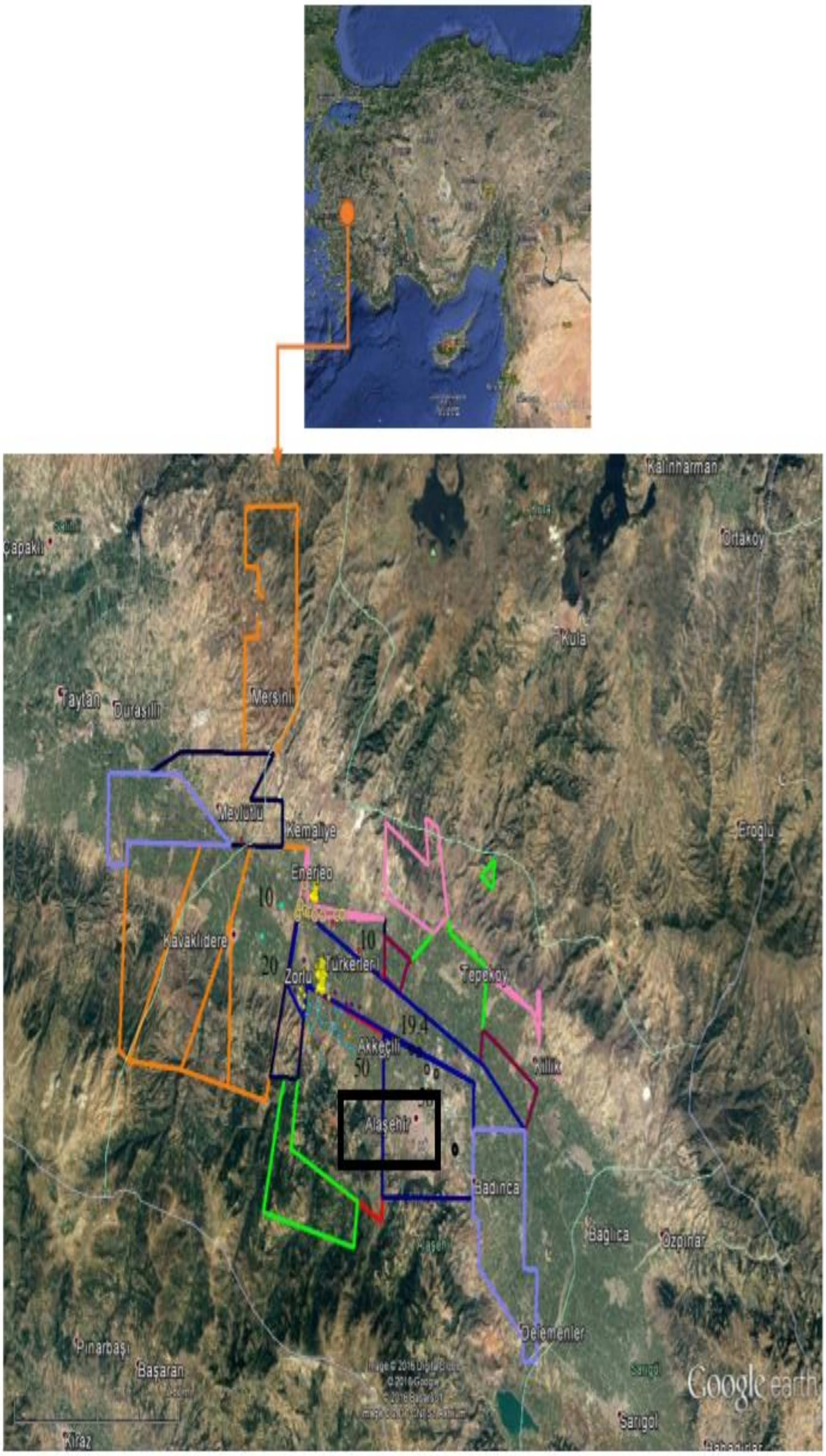

Figure 5.1 Alaşehir Geothermal Field – Study Area (Akin, 2017)

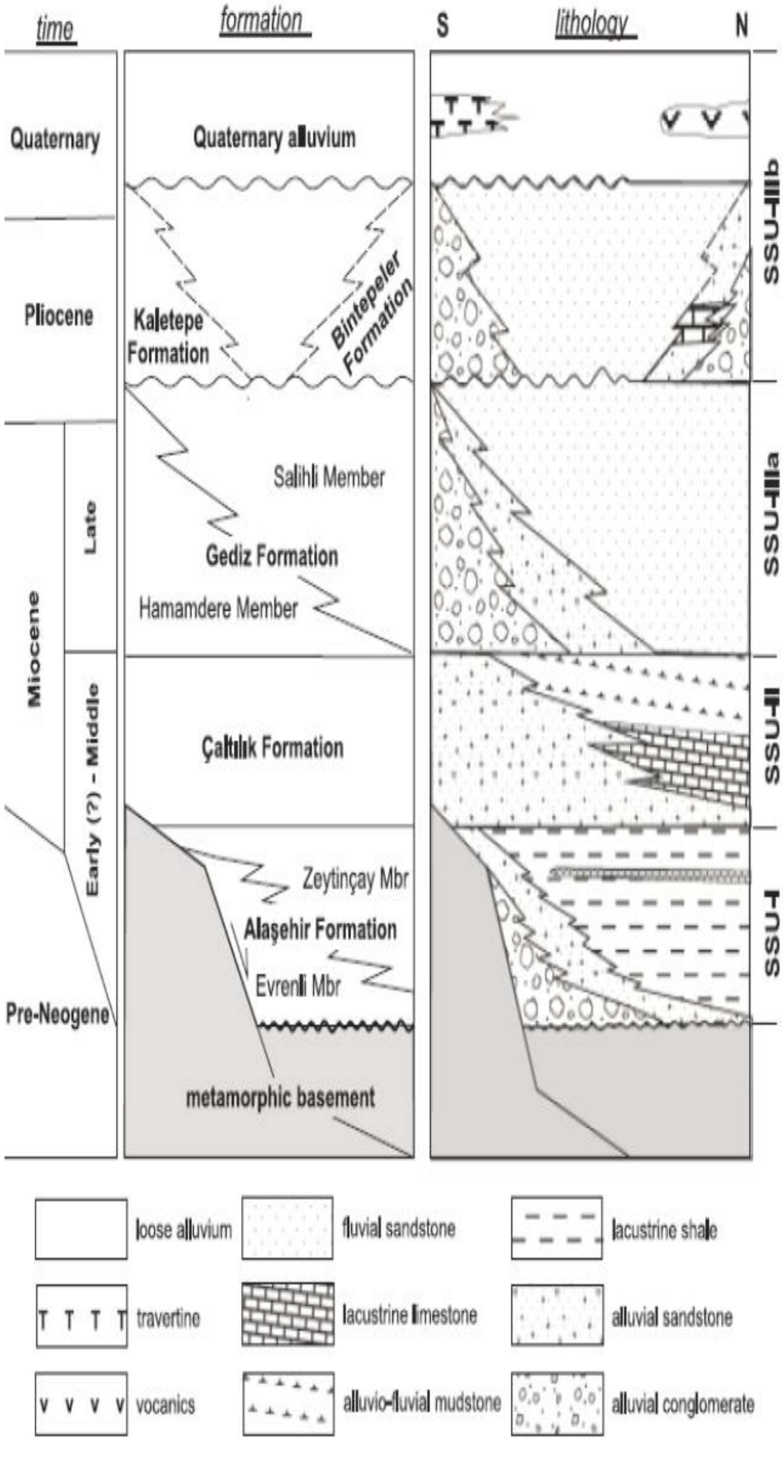

Figure 5.2 Simplified Stratighraphy of Alaşehir Geothermal Field (Ciftci and Bozkurt, 2009)

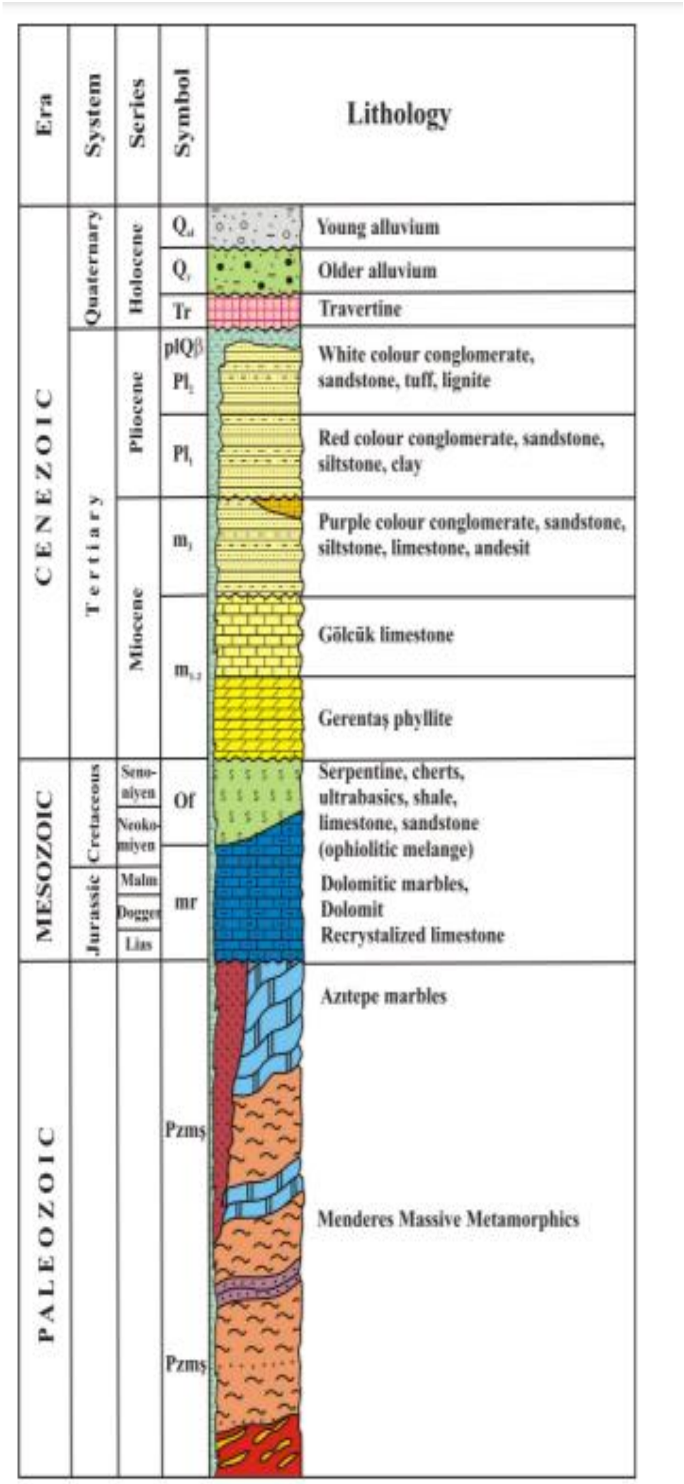

Figure 5.3 Stratigrafic Section for the Subject Area (After Yilmaz and Gelişli, 2003)

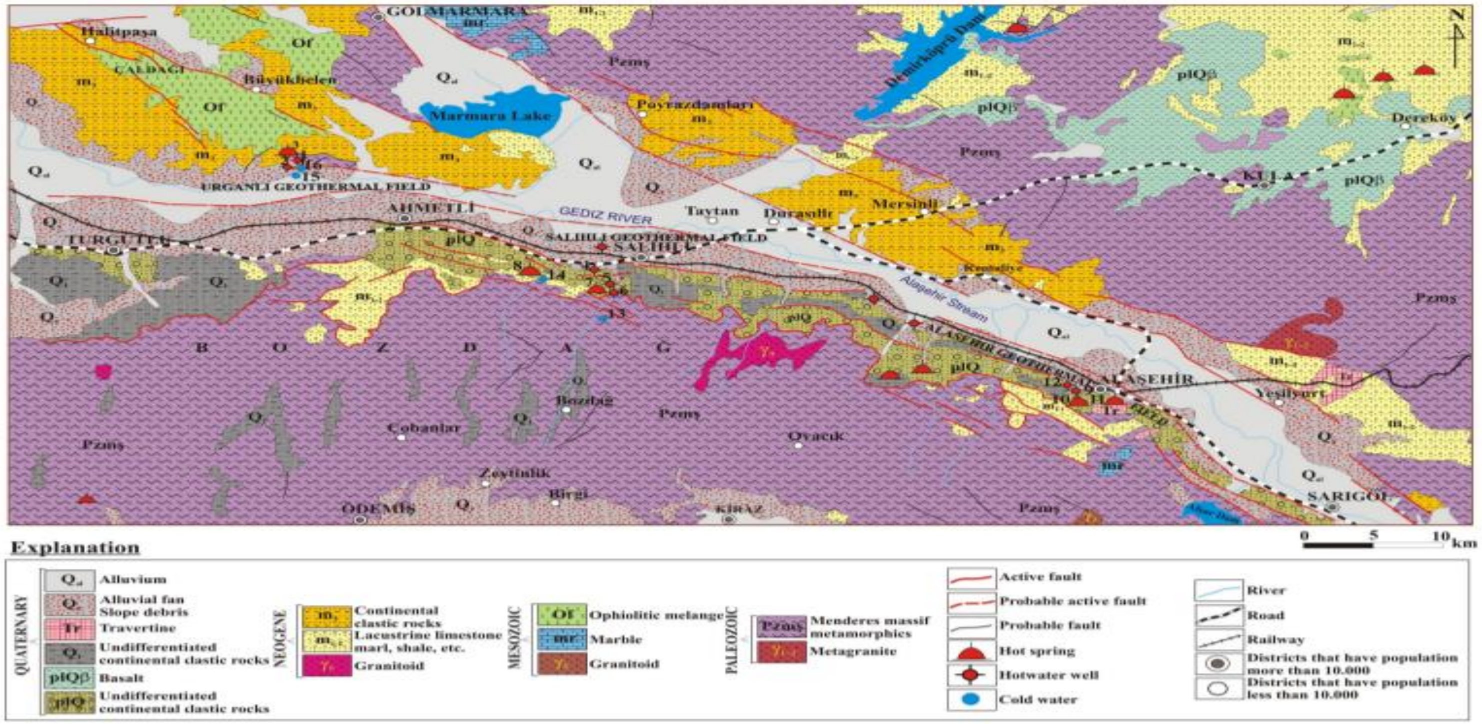

Figure 5.4 The Geological Map of Alaşehir Geothermal Field (After MTA, 2002)

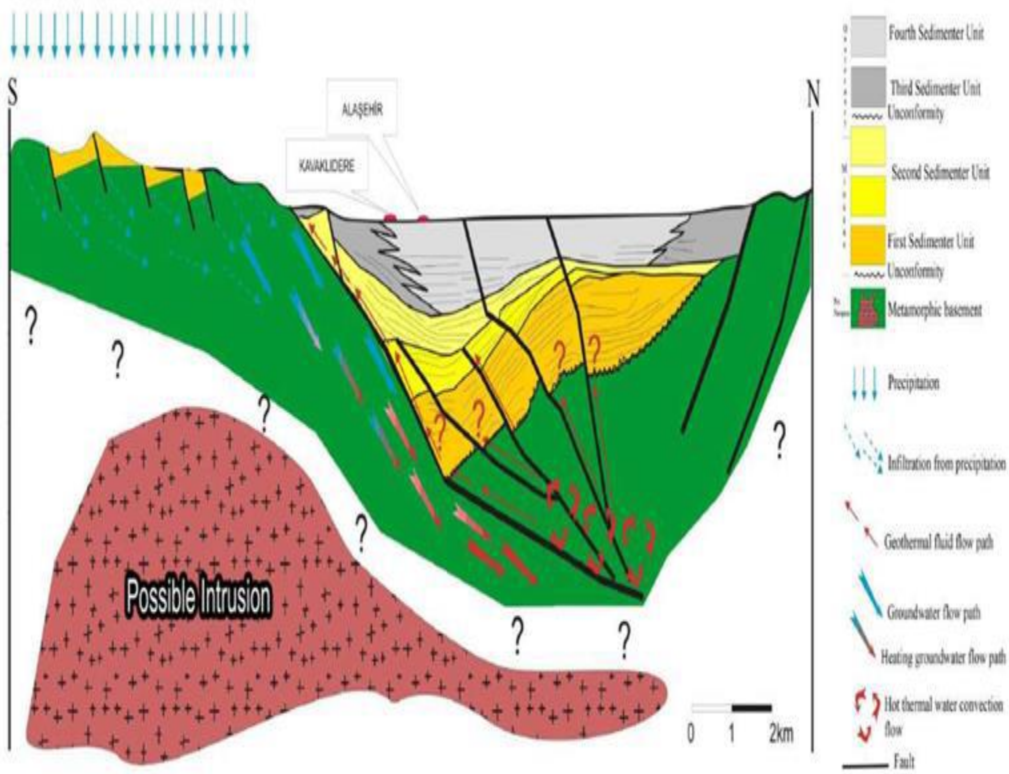

Figure 5.5 Geological Conceptual Model Created by Ciftci and Bozkurt (2009) for Alaşehir Geothermal System

CHAPTER 6

RESULTS AND DISCUSSION

In this study, five different wells have been selected from Alaşehir geothermal field. CO_2 measurements were conducted with a gas flowmeter in Wells: X-2, X-4 and X-8 and as for BY-1 and BY-2 wells, the ideal gas law is used in order to calculate CO_2 content of the produced stream. Since our estimation for the future predictions does not give a straight line, the decline rate analysis was conducted by using a non-linear least square approximation that was applied using Solver tool in Excel. Sum of squares residual is minimized by adjusting initial CO_2 content, decline rate and decline exponent. The relevant decline curves showed best matches withhyperbolic models. However, some results showed that harmonic and hyperbolic models and their decline rates are very close to each other. It was also observed that in the transient time period, production wells showed different decline behaviours based on hydraulic connectivity and proximity to injections wells. However, once the breakthrough time was reached, most of the wells showed hyperbolic decline with different exponents and initial decline rates. Decline rates and decline constant, b are given in Table 6.1 for the studied wells and it is very clear that constant b is changing between 0 and 1. Production and injection well locations are shown in Figure 6.1. In this figure, red points represent production wells while blue points represent injection wells. Injection wells are near to the production site with a minimum distance of 1 km.

Further to the above, it should be noted that while observing declines in carbon dioxide production rates, injected brine rates did not change too much during the re-injection processes. Therefore, this rate does not have an effect on these observed declines. However, more than 40% decrease in production wells was observed due to CO_2 declines. The flow rate of production wells was ranging from 300 ton per hour to 600 ton per hour at the beginning. Yet after having CO_2 declines, the maximum flow rate of production wells in the field dropped to less than 400 ton per hour.

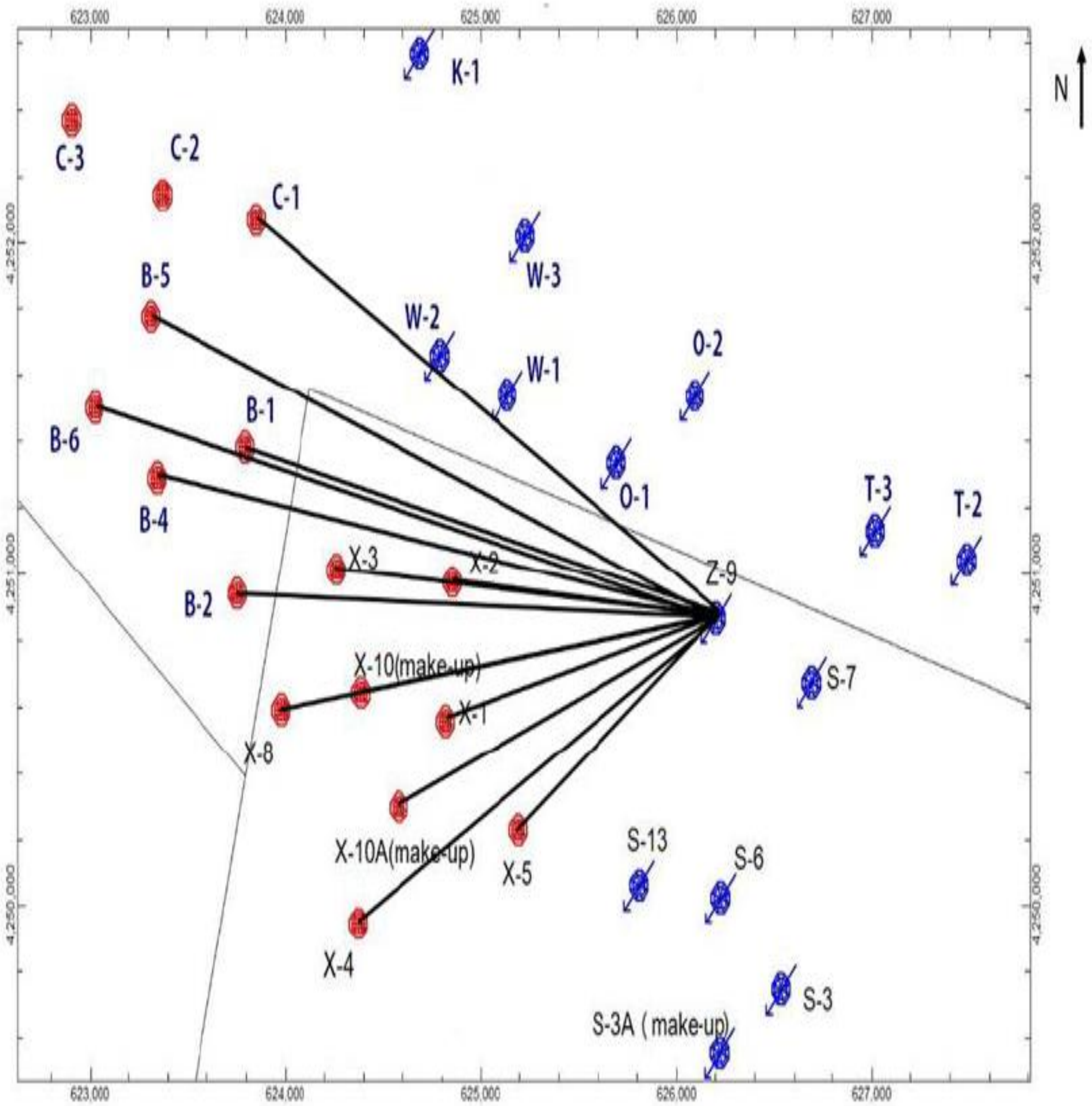

Figure 6.1 Production and Injection well locations (Aydın 2018)

Table 6.1 Hyperbolic Model Parameters

Well ID	Decline Rate (Hours)	b, Exponent (Constant)
BY-1	0.0002	0.69
BY-2	0.000043	0.31
X-2	0.00237	0.82
X-4	0.005318	0.63
X-8	0.005276	0.81

Decline curve analyses of BY-1, BY-2, X-2, X-4 and X-8 wells were evaluated and discussed as follows:

- **BY-1 Well:** From the Figure 6.2, it can be said that a gradual decline occurred in CO_2 production. BY-1 well data showed that CO_2 production amounts did not change too much in the beginning. However, a decline in CO_2 production rate has been observed since July 2016. Since, there is no big change at the beginning it could be said that this well dominantly produces from natural geothermal recharging from a deep reservoir section. Also, it was observed that re-injected brine reached BY-1 well after nearly 7 months. Since BY-1 well is relatively far from an injection well it took 7 months for re-injected brine to reach this production well.

  In addition to the above discussion, the non-linear least square results showed that best match was obtianed with the hyperbolic decline (Figure 6.4). The breakthrough time occurred at 5018 hours. It can be stated that the decline in CO_2 production amount will continue in the future. It is expected that CO_2

production amount will be around 0.13 ton per hour in January 2024 (Figure 6.3).

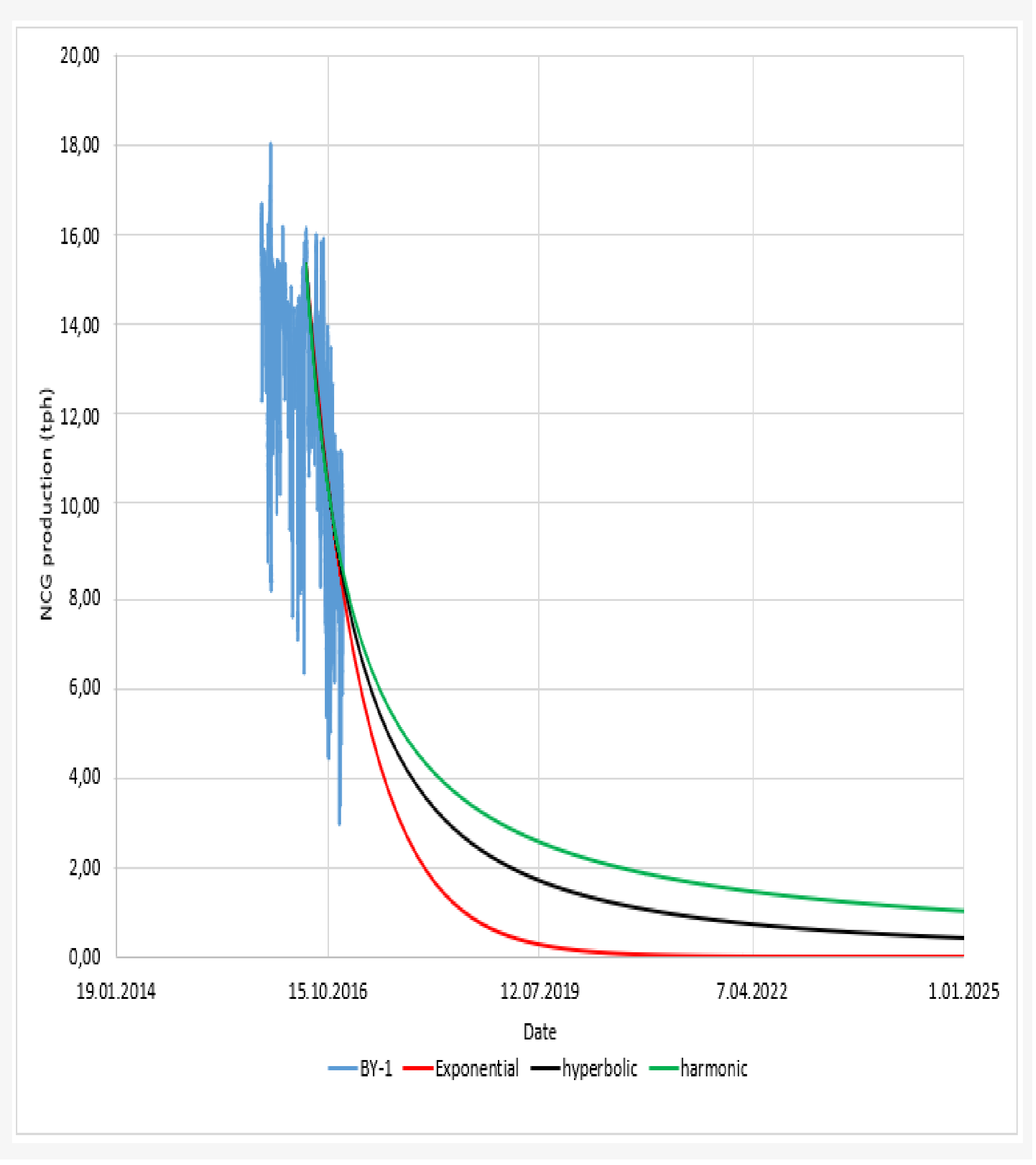

Figure 6.2 Decline Curve Analysis of Well BY-1

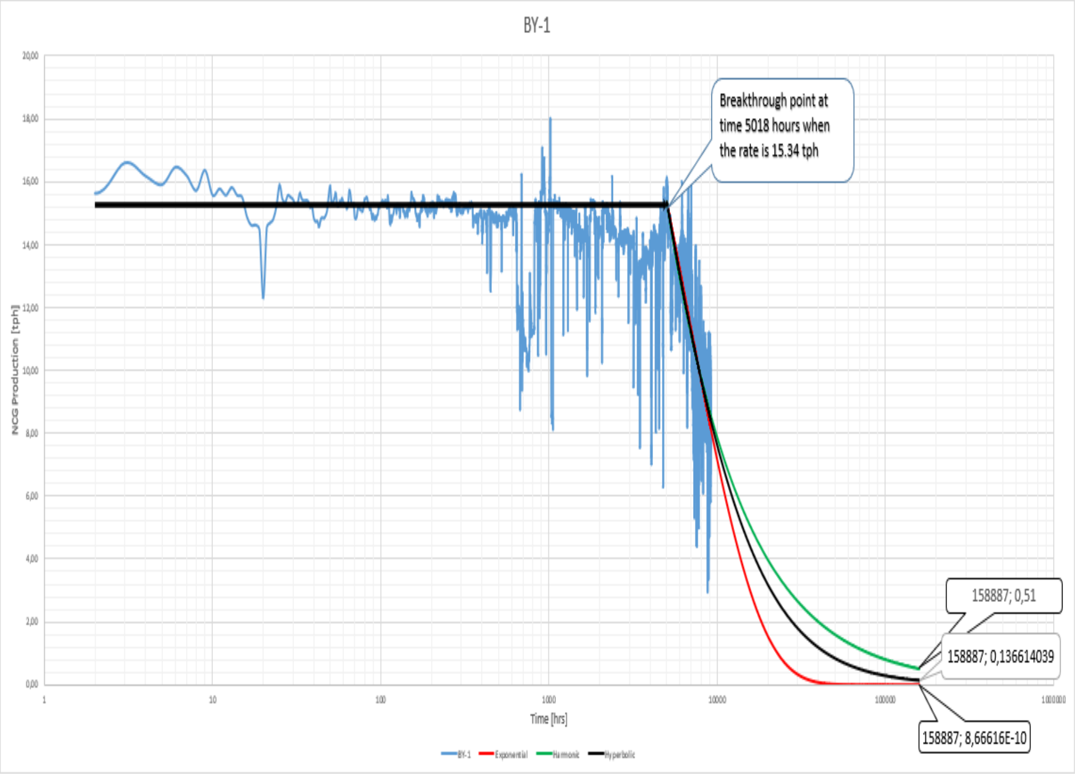

Figure 6.3 Semi-log Analysis of Well BY-1

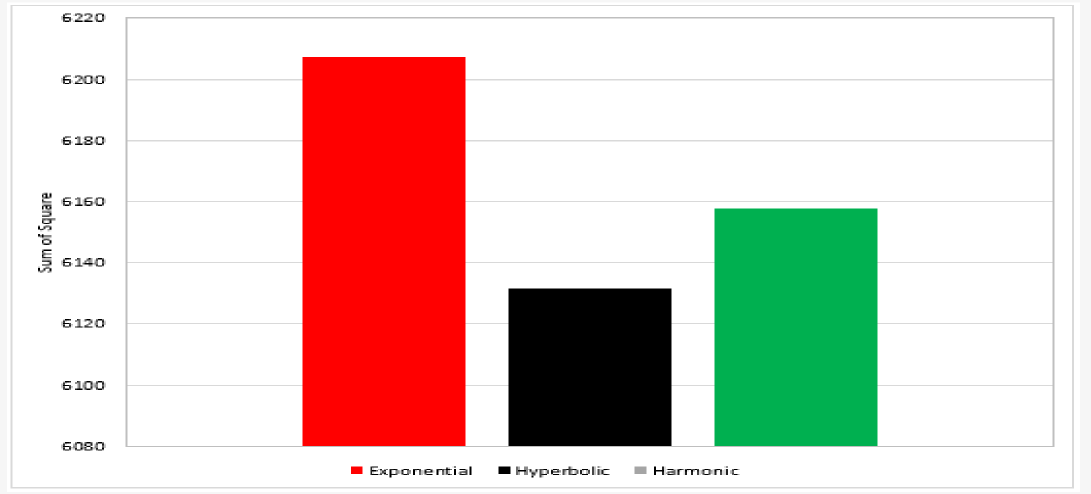

Figure 6.4 Sum of Square Bar Chart for BY-1 Well

- **BY-2 Well:** It has been observed that there is a gradual decline in CO_2 production amount (Figure 6.5). Since the CO_2 amount has been relatively steady till 5 months, this period is recorded as breakthrough time. Natural geothermal recharge, hydraulic connectivity between re-injection and production wells and proximity to the injection site might all be responsible for the gradual decline observed for BY-2 well. Since the re-injected brine took more than 5 months to reach the well, it can be said that the hydraulic connectivity is not very strong. Yet another reason for this delay could be explained bylarger size of the reservoir (i.e. larger pore volume).

  The non-linear least square results showed that match obtained with the hyperbolic decline was better than the others (Figure 6.7). It is estimated that the CO_2 production amount will decrease continuously and will reach to a value of 0.3 gas weight % in January 2023.

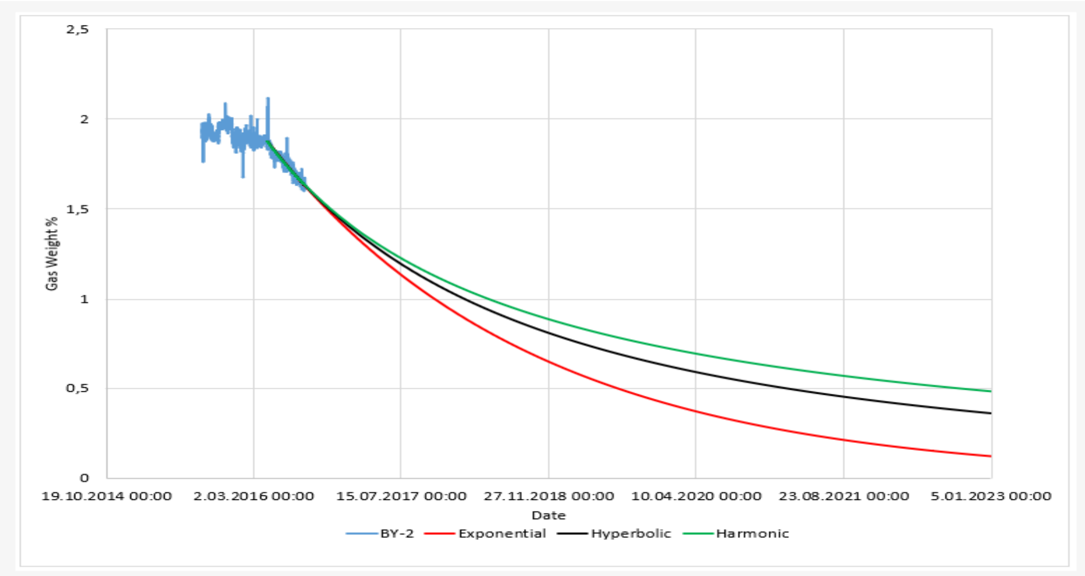

Figure 6.5 Decline Curve Analysis of Well BY-2

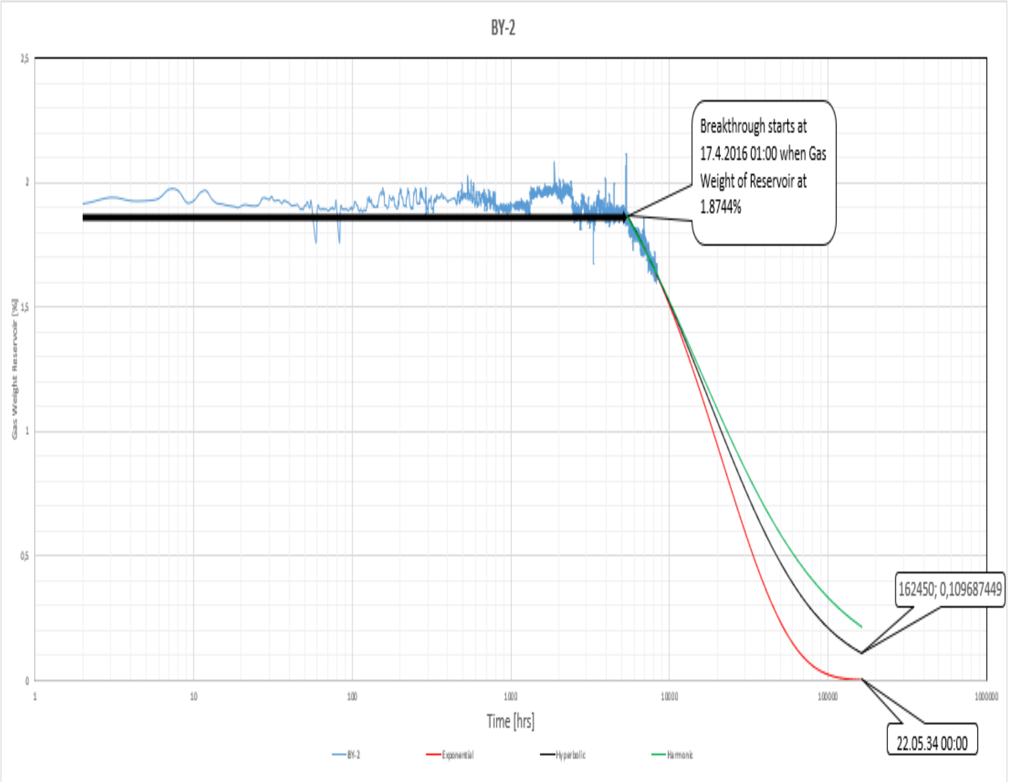

Figure 6.6 Semi-log Analysis of Well BY-2

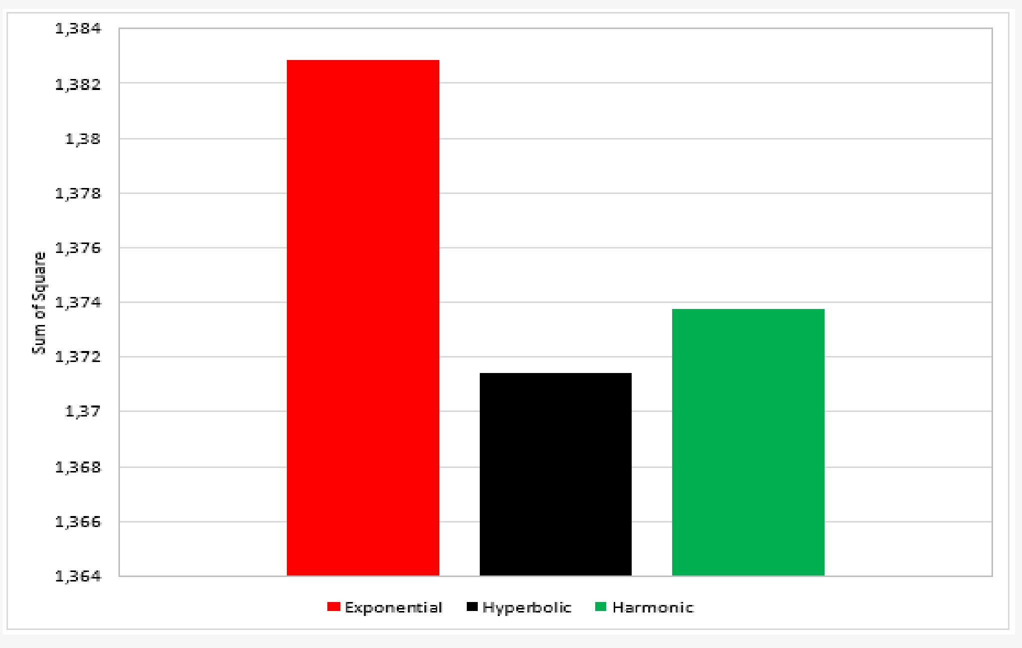

Figure 6.7Sum of Square Bar Chart for BY-2 Well

Semi-log plots of CO_2 decline were used to determine exact breakthrough time for CO_2 decline in of BY wells. After 2 years of production, when a new power plant was commissioned, a very sharp CO_2 decline was observed in two of these wells (i.e. BY-1 and BY-2).

- **X-2 Well**: A sharp decline that can be explained by a strong hydraulic connectivity between production and injection wells, has been observed in well X-2 (Figure 6.8). Apart from this strong hydraulic connectivity, low proximity to the injection site might be another reason as injection - production well distance is much more closer to the injection site when compared with that of the BY wells. Furthermore, it can be stated that CO_2 production decline rate is quite large (i.e. larger than 80%) within a few years of production.

Hyperbolic decline gived the best match for the future forecast. The expected CO_2 decline amount in December 2024 will be around 0.05 (gas weight %).

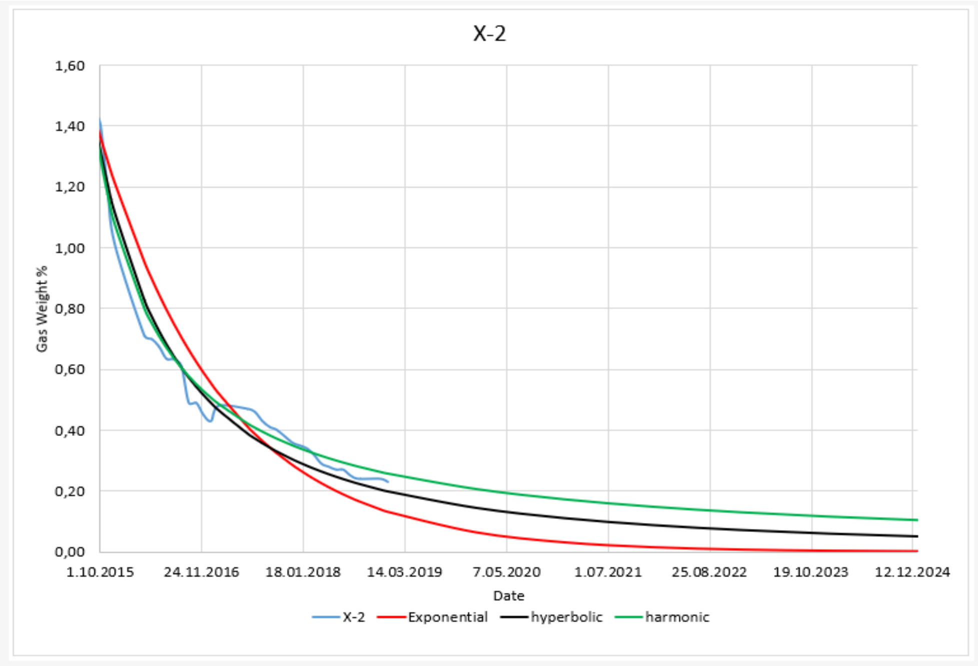

Figure 6.8 Decline Curve Analysis of Well X-2

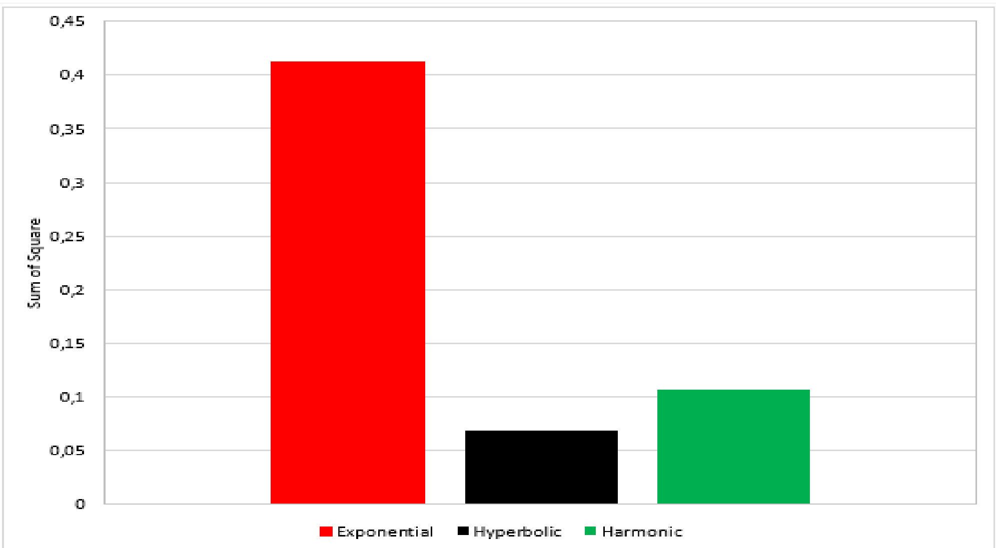

Figure 6.9 Sum of Square Bar Chart for X-2 Well

- **X-4 Well**: More than 85% of CO_2 decline was observed between the years of 2015 and 2019 (Figure 6.10). The hydraulic connectivity between injection wells and X-4 is possibly responsible for this sharp CO_2 decline. In this regard, the decline is similar to that observed in X-2 well.
  The best fitting of decline type was found to be of hyperbolic type. The future prediction of CO_2 decline will be around 0.03 (gas weight %) in January 2025. It should be noted that this amount of CO_2 decline will affect future well performance as CO_2 is one of the most important parameters for pressure support during the production life time.

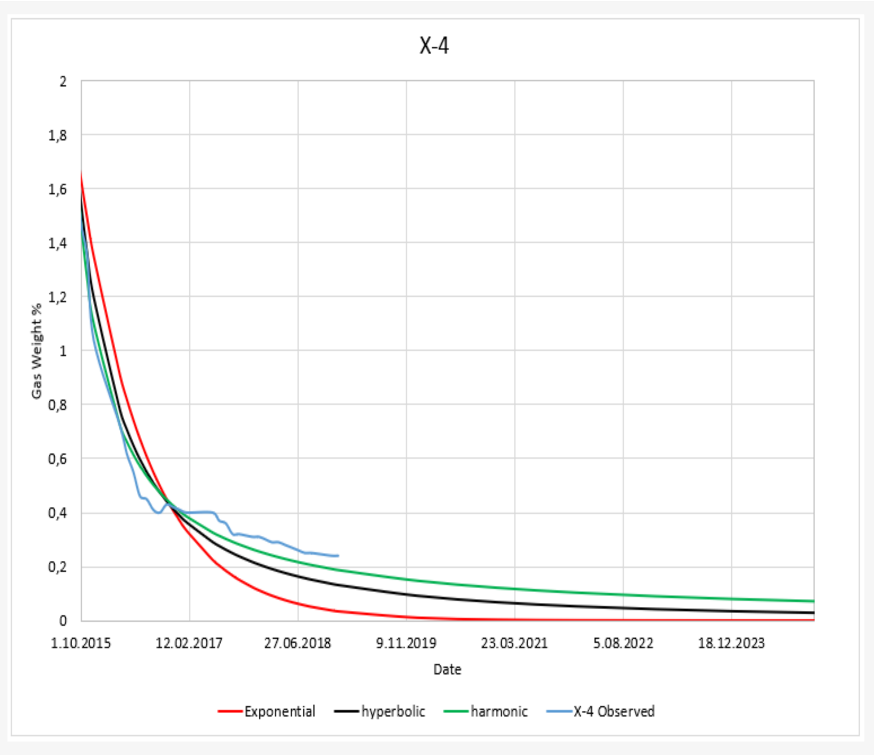

Figure 6.10 Decline Curve Analysis of Well X-4

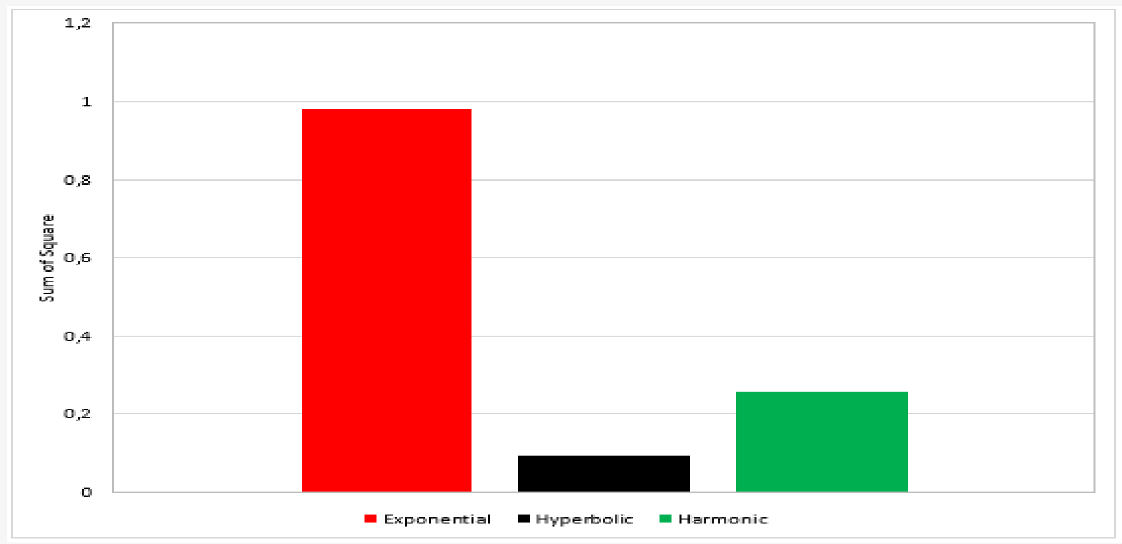

Figure 6.11 Sum of Square Bar Chart for X-4 Well

- **X-8 Well:** A sharp decline of CO_2 content for the well X-8 has been observed (Figure 6.12). This decline reveals that injected brine supports more than 80% of the production. Akın (2017) reported that 90% of tracer was recovered in production wells. This means that CO_2 decline will possibly converge to 90% decline in the future.

  Best fitting of decline was found to be of hyperbolic type (Figure 6.13). The expected CO_2 production amount in December 2023 will be around 0.07 (gas weight %).

Solution gas drive is the production drive mechanism in geothermal reservors located in western Anatolia. CO_2 in geothermal reservoirs provides additional pressure support for production wells. Thus, CO_2 decline in production wells will reduce the performance of the production wells. Therefore, it can be easily said that well inflow performance relation will be negatively affected due to this sharp decline. It is also possible to observed premature temperature decline in wells where there is a sharp CO_2 decline.

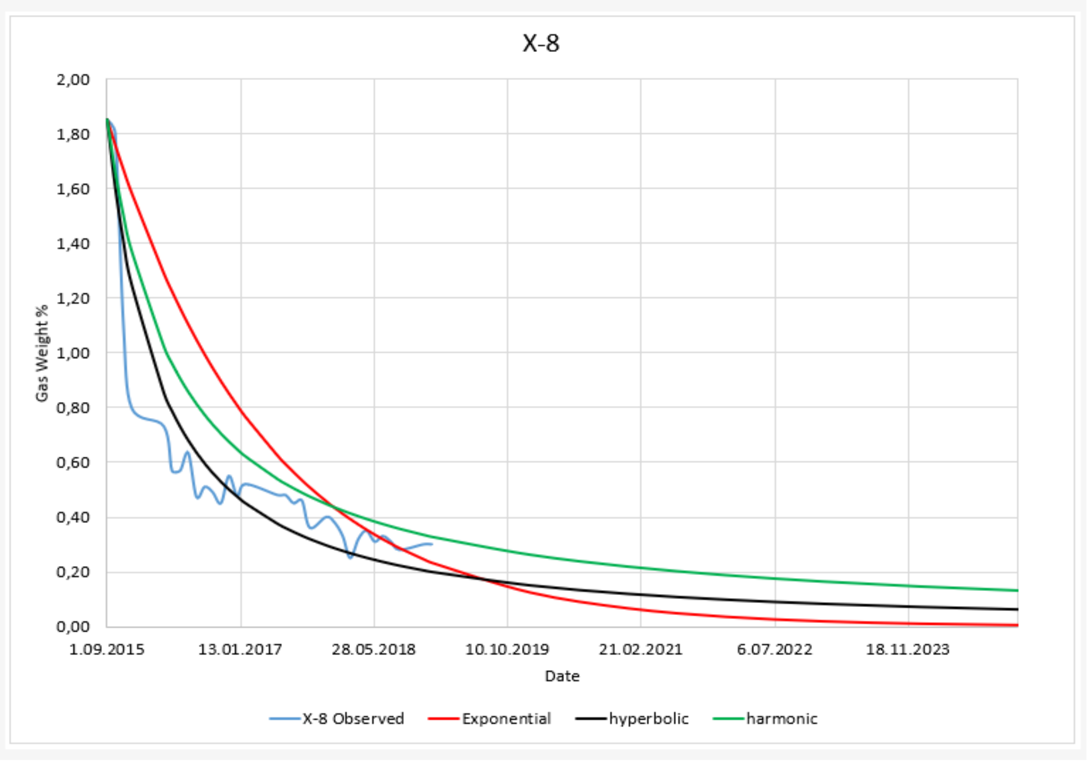

Figure 6.12 Decline Curve Analysis of Well X-8

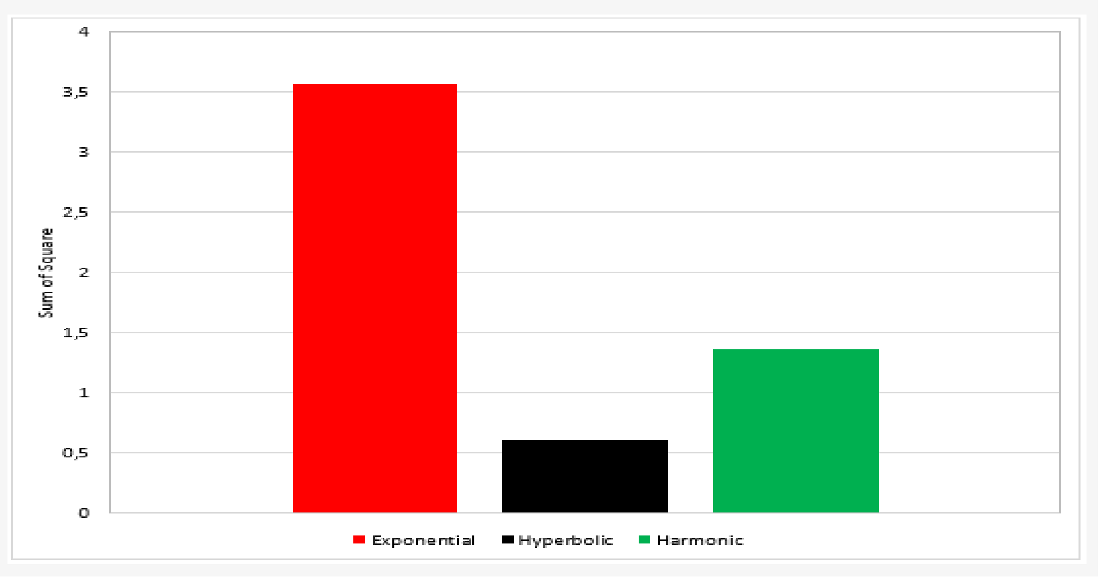

Figure 6.13 Sum of Square Bar Chart for X-8 Well

As for the observed oscillatory behaviour of CO_2 rate in the well data, it can be said that it is due to either variations in water production rate or irregular slug type of CO_2 production.

Further to above discussions, in the utilization of geothermal energy, CO_2 is separated from the geothermal fluid and it is released to the atmosphere. In Alaşehir geothermal power plant, the colder reinjection water has CO_2 concentration less than 0.2% by weight and the pH of this injectate is 9 (i.e. basic nature). Re-injection fluid tends to dissolve less $CACO_3$. In other words, the amount of dissolved CO_2 decreases as it is recirculated in the reservoir. Thus, pH values of production wells of X-2, X-6 and X-8 increased gradually (Figure 6.14). This pH monitoring also proves that there is a CO_2 decline in aforementioned X wells. Since there is no pH data regarding the BY wells, a proper evaluation cannot be conducted.

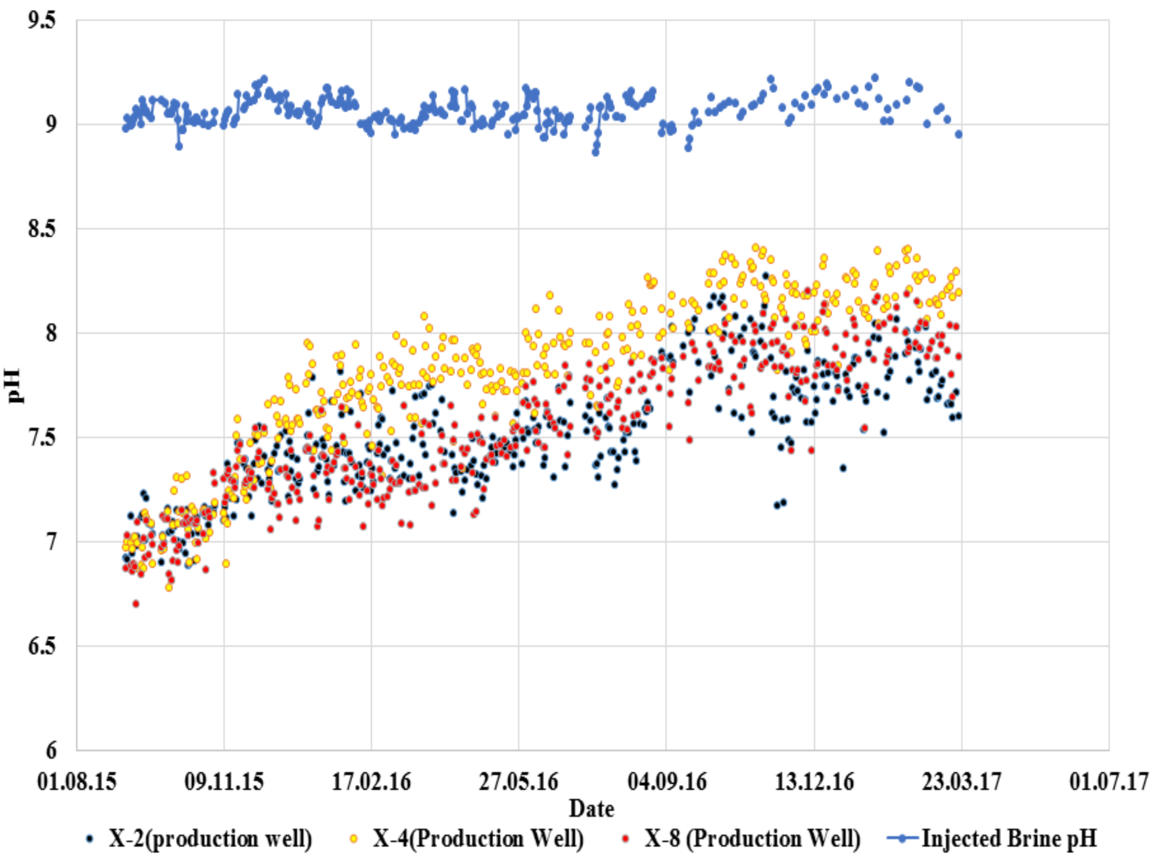

Figure 6.14 pH Values of Production Wells and Injected Brine

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

In this study, CO_2 production declines for wells located in Alaşehir Geothermal Field have been modeled. It was found that there are two types of CO_2 production decline: sharp decline that can be explained by high hydraulic connectivity and low proximity to the injection site in X wells and gradual decline observed in BY wells, which is possibly due to limited hydraulic connectivity and larger proximity to the injection site. Based on this evaluation, gradual decline has been observed in BY-1 and BY-2. On the other hand, sharp declines were observed for X-2, X-4 and X-8. Further to this, it can be said that even though there is no CO_2 decline in BY wells in the early days of the production, a gradual decline has been observed after a few months of production. Because of that, it can be said that all wells are interconnected through conductive and intercepted faults.

CO_2 production forecast that might be used as a guidance for environmental concerns or well performance for the future activities has been conducted. Based on fault characteristics and well placement, a gradual and/or a sharp decline in CO_2 production can be expected. In X wells CO_2 decline as low as 0.05 gas weight % in December 2024 is expected. It is estimated that the CO_2 production amount of BY wells will decrease continuously and will reach to a value of 0.3 gas weight % in January 2023. In line with the results obtained in this study, the re-injection and production strategy can be revised for a better reservoir management.

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