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Forecasting the coal production: Hubbert curve application on Turkey's lignite fields

Istemi Berk[a,*], Volkan Ş. Ediger[b]

[a] Department of Economics, Faculty of Business, Dokuz Eylul University, 35160 Buca, Izmir, Turkey
[b] Center for Energy and Sustainable Development, Kadir Has University, Kadir Has Street, Cibali 34083, Istanbul, Turkey

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ABSTRACT

The dependence on imported energy sources is one of the biggest challenges that Turkey and many other similar countries face in the 21st Century and the gap between production and consumption cannot be decreased without increasing the domestic production. Forecasting of domestic energy production therefore plays a vital role in order to be able to develop sound energy policies towards maintaining sustainable development. However, although this question is essential in this respect especially for import dependent countries, the previous literature is surprisingly scarce. This paper, therefore, will be important for future studies on estimation of energy production. We first analyzed lignite production of Turkish Coal Enterprises (TKI) from a historical perspective and then forecasted the future production by using the Hubbert curve, depletion rate, and decline curve methodologies. We concluded that the largest fields are about to enter a declining phase of production in upcoming years and most of the reserves will remain untapped if business-as-usual continues in the future. The methodology and interpretations may be used by other developing countries, which deeply suffer from energy import dependency.

1. Introduction

One of the biggest challenges that Turkey faces in the 21st Century is the dependence on imported energy sources (e.g., Ediger, 2001, 2004; Çamdalı and Ediger, 2007; Ediger and Berk, 2011). In 2013, only 26.5% (31.944 Million tons-of-oil-equivalent, Mtoe hereafter) of total primary energy supply (120.290 Mtoe) was produced domestically and the net import dependency of the country was 72.3% (86.978 Mtoe).[1] This huge gap between energy supply and demand should definitely be decreased in order to mitigate the overburden of imported energy. Increasing domestic production while decreasing consumption by improving energy efficiency is obviously the best way to tackle this important problem. However, both solutions appear not to be readily available because of resource scarcity and the traditional inefficiency of the Turkish energy system. The sustainability of more than a decade of economic growth and development, fueled by the increasing energy consumption of the country, depends strongly on developing and implementing sound energy policies towards solving this problem (Ediger and Tatlıdil, 2002; Ediger, 2003). This problem and possible solutions are also applicable for similar developing countries, which deeply suffer from energy import dependency.

The country's coal endowment is the most plausible candidate for increasing domestic energy production in Turkey. By 2012, remaining recoverable reserves of oil and gas were 310.4 Mtoe and 7.1 Billion cubic meters (Bcm, hereafter), respectively, whereas the country has 12,152 Million metric tons (Mtonnes, hereafter) of proven lignite and 523 Mtonnes of proven hardcoal reserves (WEC-TNC, 2015).[2] Consistently, around half of the country's domestic primary energy production in 2013 was from coal. The share of total domestic production is 7.8% (2.485 Mtoe) for oil, 1.4% (443,000 toe) for natural gas, and 1.5% (488,000 toe) for asphaltite, whereas it is 43.7% (13,973 Mtoe) for lignite and 3.1% (990,000 Toe) for hardcoal. The overall share of fossil fuels is 57.5% (18.380 Mtoe) of domestic energy production, which is only 26.6% (31.944 Mtoe) of primary energy supply (120.290 Mtoe).

The purpose of this study is, therefore, to contribute to the policy-making processes towards increasing the domestic energy supply of the country by developing a forecast for Turkey's future lignite production.

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* Corresponding author.
E-mail address: istemi.berk@deu.edu.tr (I. Berk).

[1] According to the statistics provided by the Ministry of Energy and Natural Resources of Turkey (MENR), 5.497 Mtoe was exported mostly in the form of various oil products and 3.814 Mtoe was used as bunkers in 2013 (MENR, 2015).

[2] However, most recently, Ediger et al. (2014) concluded that reserve estimation practices in the country should definitely be revised to provide a more realistic evaluation of the country's lignite potential for developing medium- and long-term energy strategies and policies for decision- and policy-makers.

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Given the role of lignite in the Turkish energy system, forecasting future production becomes vital for the country's energy supply security. An estimate for Turkey's coal production in the long run would not only help to develop accurate investment planning for energy production/generation and distribution but would also be helpful for developing policies for alternative energy sources and for climate change as noted by Rutledge (2011). In fact the problem is global and the conclusions drawn from this study will be applicable in other similar countries in the world. At present, more than 20 countries have already reached a maximum capacity in their coal production, unlike China, which has the third largest coal reserves in the world, is the largest coal producer and consumer and whose coal production has not yet reached its peak (Lin and Liu, 2010).

Although, the questions regarding future energy production and the required imports are essential in this respect especially for import dependent countries, it is surprising that literature on energy supply forecasting is considerably limited compared with that on energy demand. In most countries energy forecasting is typically carried out for the demand side of energy systems and forecasts of both energy production and consumption such as the one carried out by Xiong et al. (2014) in China are rare.

Turkey is no exception. The studies on energy demand forecasting in Turkey date back to the 1960s and were mostly carried out by the State Planning Organization (SPO), the Ministry of Energy and Natural Resources of Turkey (MENR) and a number of academicians.[3] On the other hand, to the authors' best knowledge, Ediger et al. (2006) is the first study on forecasting production of fossil fuel sources in Turkey, including hard coal, lignite, asphaltite, oil, and natural gas from 1950 to 2003. In addition to this study, Toksarı (2009) estimated Turkey's net electricity energy generation and demand until 2025 based on economic indicators by using the ant colony optimization (ACO) approach. Çınar et al. (2010) estimated the production of hydropower until 2012 by using genetic algorithms (GA).

The current paper contributes to the energy supply forecasting literature by concentrating on the Turkish lignite industry and by using Hubbert's methodology[4] on the comprehensive lignite mine data of Turkish Coal Enterprises (TKI, hereafter). The structure of this article is as follows. Section 2 provides a review of the relevant literature. Section 3 explains the data employed in this study. The subject of Section 4 is forecasts of future production as well as the depletion and decline curve analyses. Finally, Section 5 concludes.

2. Methodology

2.1. Forecasting fossil fuel production

Literature on estimation of fossil fuel production started as early as 1909 and the quantitative understanding of oil depletion through calculating the exhaustion time of oil reserves and different methodologies have been applied to forecast fossil fuel production curves in many regions or countries in the world since then.[5] These methods have recently been grouped into two classes, namely, (1) Top-down: models that forecast aggregate production through some form of extrapolation of aggregate variables, such as simple curve-fitting, system dynamic simulations and macroeconometric models, and (2) Bottom-up: models that represent the supply chain of the upstream oil industry, and forecast aggregate production as the sum of production from smaller units (Jakobsson et al.., 2012, 2014). Moreover, Chavez-Rodriguez et al. (2015) divided oil production forecasting techniques into three main categories namely, the economic, the geophysical based, and the hybrid, which combines the first two approaches, aiming at explaining the deviations of the geophysical models from the historical production. On the other hand, Brandt (2010) after examining all methods concluded that "the greatest promise for future developments in oil depletion modeling lies in simulation models that combine both physical and economic aspects of oil production."

2.2. Hubbert curve methodology

Hubbert method is one of the top-down methods and as correctly noted by Saraiva et al.., "among them the curve-fitting models, especially the approach of Hubbert, are a simple and suitable tool for first-order projections of future production", "especially when data for ultimately recoverable resources (URR) are uncertain and producers are price-takers" (Saraiva et al., 2014).

M.C. King Hubbert, an American geophysicist, estimated the future US oil production in 1956 by using mathematical equations (Hubbert, 1956) and later related his graphical predictions for cumulative production over time to a logistic curve (Hubbert, 1959). His famous approximately symmetric, bell-shaped curve, which is now known as Hubbert's curve, and his methodology have been debated vigorously since then (Tao and Li, 2007; Bardi, 2009). Although the methodology was initially used for oil production, later it began to be applied for other fossil fuels such as natural gas and coal. Authors such as Ericsson and Söderholm (2010), Giraud et al. (2010), Vaccari and Strigul (2011), Giraud (2012), Rustad (2012), Zittel (2012), Scholz and Wellmer (2013), Scholz et al. (2014), and Vaccari et al. (2014) have attempted to use the Hubbert's method for various mineral commodities production and techniques. Ericsson and Söderholm (2010) noted that "the differences between oil and minerals should neither be overstated nor ignored." (p. 1) and "the most important difference is clearly the recyclability of minerals but from most other points of view the differences between oil and other minerals should not be exaggerated." (p. 2).

At present, Hubbert's curve is used for many purposes varying from predicting production at a global level to country level or even to field level. However, its most common usage has always been to determine the date of the global oil peak (e.g., Bentley et al., 2007; Bardi, 2009; Reynolds, 2014). Several modified forms have been used to determine ultimate oil recovery rates of production in various countries for several resources such as oil in the USA (Kaufmann, 1991; Cleveland and Kaufmann, 1991; Pesaran and Samiei, 1995), oil and natural gas in Denmark (Mackay and Probert, 1995), oil in Brazil (Saraiva et al., 2014), natural gas in China (Wang and Lin, 2014), natural gas in Algeria (Guseo et al., 2015), oil in Peru (Chavez-Rodriguez et al., 2015), oil in Norway and Denmark (Sällh et al., 2014), oil in the UK and Norway (Fiévet et al., 2015). On the other hand, Söderbergh et al. (2010) made a field-by-field study of 83 Russian giant gas fields in order to analyze future Russian natural gas production for European energy security. A good analysis of the performance of supply forecasting over the past two decades, including the methodological errors in the geophysical models and the difficulties of creating a valid microeconomic model can be found in Lynch (2002).

Mainly four assumptions are included in Hubbert's mathematical model, namely (1) yearly production is modeled as the first derivative of the logistic function, (2) production profile is symmetric, (3) production follows discovery with a constant time lag, and (4) production increases and decreases in a single cycle without multiple peaks (Brandt, 2010, p. 3959; Vaccari et al., 2014, p. 136). The validity of these assumptions was often criticized, but as Hubbert noted frequently in his publications, these were only simplifying assumptions to allow tractable mathematical analysis, not a reflection of reality

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[3] Please see, Ediger and Tatlidil (2002) for a comprehensive literature review of demand forecasts in the Turkish energy system. Since then, various techniques have been applied in energy demand forecasting for Turkey, such as degree-day, linear and multivariate regression, autoregression, genetic algorithm, and artificial neural network (Ediger and Akar, 2007).

[4] Authors are aware of the intensive debate on the plausibility of the assumptions of Hubbert's methodology. Please refer to Section 2.2 for the literature review on this debate and the reasoning of the choice of this methodology in the current paper.

[5] For a comprehensive summary please refer to Brandt (2010) and Saraiva et al. (2014).

(Brandt, 2010, p. 3959–3960).

It is obvious that the Hubbert's model essentially assumes geology as the prime constraint for discovery and production, ignoring other important economic, technological, and political factors (e.g., Ericsson and Söderholm, 2010; Vaccari et al., 2014). Because of these drawbacks in methodology, subsequent use of Hubbert's approach was not always successful (e.g., Sorrell and Speirs, 2010).

For instance, Rustad (2012) warned that the type of production curves may change through time depending on several factors. Analyzing the production histories of seventeen raw materials, he concluded that “Although many of these resources have exhibited logistic behavior in the past, they now show exponential or super-exponential growth. In most cases, the transition has occurred in the last ten to twenty years.” (p. 1903). Ericsson and Söderholm (2010) emphasized the importance of economic factors such as the underlying causal relationships in the supply and demand, by noting that “Long before the last ounce of metal is extracted from the earth's crust, costs would rise, at first curtailing but eventually completely eliminating demand. In other words, what we could fear is not physical depletion, where we literally run out of mineral resources, but economic depletion, where the costs of producing and using mineral commodities increase to the point where no one longer is willing to buy them.” (p. 1). For example in the case of asbestos, a nearly ideal peak curve is obtained not because the asbestos reserves are completely ran out but because it is outlawed, meaning there is no market anymore (Zittel, 2012).

The method, however, can be used in special cases. Studying the Hubbert's thesis on mineral commodities production peaks, Giraud (2012) concluded that this thesis can be used if “it can be proven that neither the exploration efforts nor the time lag between discovery and production are sensitive to price variations” and if “the peak has already occurred” (p. 22 and 26). Scholz and Wellmer (2013) concluded that this methodology is not appropriate for predicting the future availability of production, unless this view is not substantiated; (1) by taking a historic resource economics perspective while introducing a dynamic view on the multiple geological, socio-economic and technological dynamics that are involved in resource exploitation and (2) by referring to standard geological knowledge and data.

In spite of all these critiques, the question “why then did Hubbert so successfully forecast the peak of production of oil in lower 48 state in the US? ” remains to be answered. Giraud et al. (2010) attempted to answer this question as “a Hubbert’s type peak oil can appear in specific oil provinces, if these provinces progressively appear to be less favorable to exploration than others.” (p. 17). Vaccari et al. (2014) stated that “The predictions of the Hubbert modeling approach might best be examined as a conceptual model to describe one scenario for how future production might play out. It could also be useful as a stage in the development of such models, as criticism may lead to the incorporation of more factors, so one may judge what the potential impact of them may be” (p. 136). Scholz et al. (2014) also acknowledge that “the Hubbert curve may show high validity dynamics for US oil production (if we exclude unconventional forms of oil production such as oil shale production)” (p. 31). It can also be used successfully for limited resources with a supply market structure (Scholz and Wellmer, 2013).

There seems to be a consensus in the literature that Hubbert curve has a number of shortcomings especially when it comes to forecasting global production. One obvious reason is that global production of resources is strongly affected by price variations, i.e. both current and future expected prices. Yet, it is also stated in the literature that the reason why Hubbert's own application on oil production in Lower 48 state of the USA turned out to be a reasonable approximation is that, it was based on individual provinces.

Similarly, the paper at hand is applying the Hubbert's methodology on a data set of lignite production in individual fields owned by state-owned coal mining company of Turkey, TKI. The period under investigation provides the authors a unique opportunity to apply Hubbert's curve methodology as during this period the lignite market has been strictly dominated by state-owned companies and therefore the economic conditions such as prices were not important factors in production decision. Moreover, because of the fact that, lignite is the only significant national fossil fuel in the country, in order to decrease energy import dependence, it has been a major policy for Turkish governments to produce as much as the geology of the fields allows. Hence, the authors of the current paper believe that in spite of all the shortcomings, the Hubbert's method for forecasting future lignite production in the fields of Turkey is still one of the most appropriate techniques. On the other hand, as stated correctly by Brandt (2010) future of the depletion/peak resource methodologies lies in simulation models, which considers both physical and economic aspects.

2.3. *Application of Hubbert's curve in coal production*

Hubbert's curve, which was originally developed for oil, has begun to be applied for other fossil fuels such as coal and also natural gas production lately. Although some people think that coal supply only depends on the economic cost and technological factors, but do not consider the life cycles of coal fields, some others such as Tao and Li (2007), who used the generic STELLA model to simulate Hubbert's Peak for Chinese raw coal production, demonstrated that this model is robust. This means that the production of coal fields also displays a bell-shaped curve with a gradual increase to maximum, a short peak, and a gradual decline. Lin and Liu (2010) by using logistic curves and Gaussian curves to predict China's coal peak, showed that the coal production peak will be between the late 2020s and the early 2030s. On the other hand, Wang et al. (2013) performing a comprehensive investigation in order to determine the shortcomings of the previous reports concluded that the inevitable coal peak in China appears as early as 2024.

Similar to oil, determination of the global peak has recently become one of the most important topics in coal research. Mohr and Evans (2009) developed a model to determine the ultimately recoverable resources of coal and also the possible Hubbert's peaks by including supply and demand interactions. After they applied their model to all coal producing countries, they found that worldwide coal production will peak between 2010 and 2048 on a mass basis and between 2011 and 2047 on an energy basis. Höök et al. (2010) found that a global peak in coal production can be expected between 2020 and 2050, depending on estimates of recoverable volumes by using a logistic model. They also concluded that global coal production could reach a maximum level much sooner than most observers expect. Criticizing the estimation of the world's coal production from reserves that are calculated from measurements of coal seams, Rutledge (2011) showed that where the estimates based on reserves can be tested in mature coal regions, they have been too high, and that more accurate estimates can be made by curve fits to the production history. Maggio and Cacciola (2012) used a predictive model based on a variant of the multi-cyclic Hubbert approach to forecast future trends in world fossil fuel production, including oil, natural gas, and coal. They started from historical data on these fossil fuels and taking into consideration three possible scenarios for the global Ultimate (i.e. cumulative production plus remaining reserves plus undiscovered resources), they determined when these important energy sources should peak and start to decline.

2.4. *Methods used in this study*

In this paper, the future lignite production is estimated by using Hubbert's rate-of-production curves by employing the methodology proposed by Hubbert (1956). According to Hubbert, cumulative production from an exhaustible resource over time ($Q(t)$) follows a logistic growth curve:

$$Q(t)=\frac{Q_{max}}{(1+ae^{bt})}$$

Where, Q_{max} is the total resource available and a and b are constants. As correctly noted by (Ediger et al., 2006), it is obvious that the forecasts should be compatible with the estimated reserves, which means the area under the "rate-of-production curve" of Hubbert is equal to "ultimate cumulative production" or "ultimate recoverable reserve" (Hubbert, 1982). In this respect, constants a and b are of significant importance. For instance, Hubbert (1956) using US oil production data determined the values of a and b to be 46.8 and −0.0687, respectively. In this paper, we determined different a and b values for different lignite fields given the best-fit to historical production data.

One of the most important characteristics of this methodology is that cumulative production is symmetric with a mean value of q_{max}, maximum/peak annual production, which is calculated as follows:

$$q_{max}=\frac{Q_{max}\mid b\mid}{4}$$

The year of peak production, furthermore, is calculated by,

$$t_{max}=\frac{1}{b}\bullet\ln\left(\frac{1}{a}\right)$$

We also applied the exponential decline curve (Arps, 1945; Höök et al., 2009) and depletion rate curve (Höök, 2009) methodology to the data of some lignite fields, which are already in decline phase, in order to predict prospective production and historical depletion. Arps (1945) describes exponential decline curve analysis as follows:

$$q(t)=q_0e^{-\lambda(t-t_0)}$$

where, $q(t)$ is production at t, q_0 is production at peak time t_0 and λ is the decline rate. Using this formula we can also derive cumulative production at time t as:

$$Q(t)=Q_0+\frac{q_0}{\lambda}\left(1-e^{-\lambda(t-t_0)}\right)$$

where, Q_0 is the cumulative production at peak time. Moreover, Höök (2009) defines the depletion rate at time t as:

$$d_{\delta t}=\frac{q_t}{R_{rt}}=\frac{q_t}{R_0-Q_t}$$

Where, q_t is the production at time t, R_{rt} is the remaining recoverable reserve defined as initial reserve (R_0) minus cumulative production at time t (Q_t).

Although these methods have, to date, been applied to oilfields, there is no reason not to use them in future production estimations of lignite fields. For this purpose we have used the data of Turkey's largest lignite producer, TKI. The next section explains the data in detail.

3. Data: TKI's lignite production

From its establishment in 1957 to 2010, twenty different enterprises have participated in the production activities of TKI (Table 1). The number of enterprises, which started operations in the 1950s is 1, in the 1960s is 3, in the 1970s is 7, in the 1980s is 2, and in the 1990s is 7. The maximum number of enterprises which started operations is 5 in 1979, 2 in 1990, and 2 in 1997. The operations continued in 9 of them in 2010 whereas 6 were closed in 2002 and 2 were closed in 1989. The average operation life of these enterprises is 21.48 years while the average annual and average cumulative productions are 2.35 million tons and 62.27 million tons, respectively (Ediger, 2014).

The enterprises can be grouped based on the average production and the operation life into three groups: (1) ELI and GLI with 6.9–8.7 million tons and 32–53 years and, (2) SLI, YLI, GELI, and AEL with 4.48–6.55 million tons and 16–25 years, and (3) the remaining 14 enterprises with 0.02–0.94 million tons and 5–38 years. The range of cumulative productions of the first group is 287.0–372.4 million tons, the second group is 94.1–137.5 million tons, and the third group is 0.15–29.9 million tons. The largest two enterprises, GLI (29.91%) and ELI (23.05%), are responsible for more than 50% of TKI's cumulative lignite production, which is 1.245 billion tons.

GLI is the largest enterprise of TKI in terms of cumulative production. It was established under the authority of Etibank in 1940 and was later transferred to TKI in 1957. The cumulative production of GLI in its 54 years is 372.43 million tons of which 81.24% (302.58 million tons) is from surface mines and 18.76% (69.85 million tons) is from underground mines. GLI's historical production curve shows two distinct trends before and after 1990, when its biggest field, Seyitömer, was taken over by a newly established enterprise named SLI (Fig. 1). During the pre-1990 period, GLI's production increased gradually from

Table 1
Properties of the largest TKI enterprises, 1957–2010.

Enterprise	Period of Operation			Production (Million Tons)	
	Beginning	End	# of Years	Aver. Annual Production	Life-time Cum. Production
GLI: Garp Linyitleri Isletmesi.	1957	2010	53	6.90	372.43
ADL: Alpagut-Dodurga Linyitleri Isletmesi	1964	2002	38	0.31	12.07
OAL: Orta Anadolu Linyitleri Isletmesi	1966	2000	34	0.83	29.11
SLI/DLI: Sark/Dogu Linyitleri Isletmesi	1969	2002	33	0.13	4.41
AEL: Afsin-Elbistan Linyitleri Isletmesi	1974	1994	20	4.48	94.11
ELI: Ege Linyitleri Isletmesi	1978	2010	32	8.70	287.00
CLI: Çan Linyitleri Isletmesi	1979	2010	23	0.83	19.19
BLI/MLI: Bursa/Marmara Linyitleri Isletmesi	1979	2010	31	0.94	29.94
KLI: Konya Linyitleri Isletmesi	1979	1989	10	0.44	4.85
GALI: Guney Dogu Anadolu Linyitleri İşletmesi	1979	2002	23	0.29	6.91
BLKI: Bolu Linyitleri Isşletmesi	1979	1989	10	0.26	1.58
SKLI: Sivas-Kangal Linyitleri Isletmesi	1980	1988	8	0.02	0.15
GELI: Guney Ege Linyitleri Isletmesi	1985	2010	25	4.99	129.66
SLI: Seyitomer Linyitleri Isletmesi	1990	2010	20	6.55	137.51
ILI: Ilgin Linyitleri Isletmesi	1990	2010	20	0.36	7.47
YLI: Yenikoy Linyitleri Isletmesi	1994	2010	16	6.29	106.90
TLI: Trakya Linyitleri Isletmesi	1995	2010	15	0.03	0.24
KELI: Keles Linyitleri Isletmesi	1997	2002	5	0.09	0.54
GOLI: Goynuk Linyitleri Isletmesi	1997	2002	5	0.18	1.05
OLI: Oltu Linyitleri Isletmesi	1998	2002	4	0.04	0.22
Average			21.48	2.35	62.27

Notes: Note that due to data restrictions in this table all numbers are up to the end of 2010. Moreover, EKI produces only hard-coal and has been actively operating under TTK since 1983, thus it is not taken into consideration. Lastly due to data restrictions some of the enterprises are not provided.

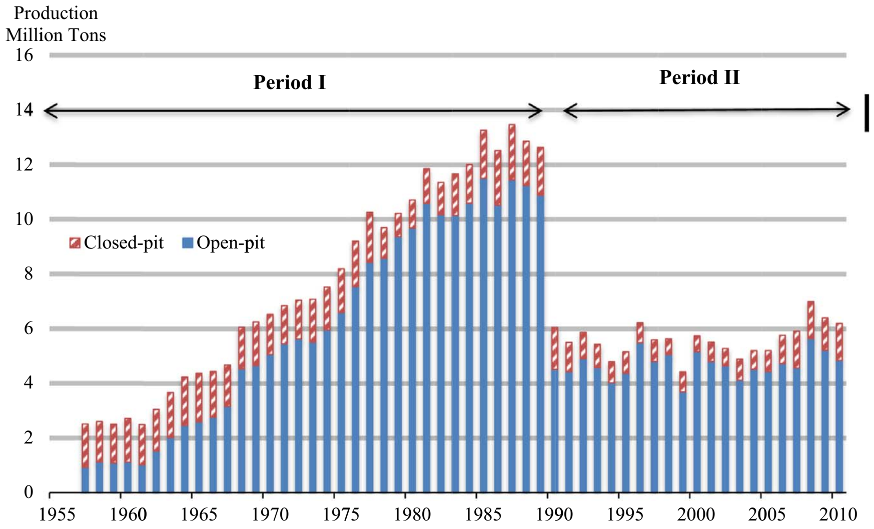

Fig. 1. GLI's open-pit and underground lignite production, 1957–2010.

2.5 million tons in 1957 to 12.63 million tons in 1989 and then after a sharp decline to 6.05 in 1990 it continued by fluctuating between 4.43 and 7.00 million tons until it reaches 6.19 million tons in 2010. The major variation in the total production was mostly due to changes in surface mining, such that pre-1990, while the underground production remained relatively stable between a minimum of 0.85 million tons and a maximum of 2.01 million tons, surface production increased significantly from 0.93 million tons in 1957 to 10.88 million tons in 1989. After the detachment of SLI, a sharp decline occurred in surface production, which decreased by nearly 60% to 4.52 million tons in 1990.

ELI, which is the second biggest enterprise in terms of cumulative production, started operations in 1978 with 1.47 million tons production, of which 986,700 t is from surface and 483,300 t is from underground (Fig. 2). Its production curve can be separated into three periods: (I) 1978–1988 with a peak of 7.44 million tons in 1984, (II) 1989–2004 with a peak of 13.14 million tons in 1999, and (III) 2005–2010 with a peak of 14.86 million tons in 2008. They can, in general, be considered as a three cyclic pattern in ascending order.

Although the underground production in this enterprise is more or less the same in the first two periods, it increased during the third period. While the underground production constituted only 9.7% of the cumulative production in the first and second periods, it increased to 46.2% in the third period because underground mines began to be operated by third-party contractors following 2005.

Among the individual lignite fields of TKI, the largest ones, which have cumulative production of more than 100 million tons from 1957 to 2010, are Seyitomer (234.81 million tons), Tuncbilek (193.67 million tons), Soma (154.41 million tons), and Milas (130.26 million tons) (Table 2). The average annual productions of these fields are also the highest with values of 4.60 million tons in Seyitomer, 4.07 million tons in Milas, 3.59 million tons in Tuncbilek, 2.61 million tons in Soma. Moreover, the largest remaining reserves are in Eynez (360.99 million tons), Tuncbilek (272.41 million tons), Milas (262.37 million tons), Denis (160.19 million tons), and Seyitomer (147.42 million tons). However, all the fields, with the exception of Eynez, had their global peak production in various years before 2010; three fields had their peaks in the 1980s, three in the 1990s, and four in the 2000s. In addition, five fields are currently in decline, six fields are questionable but possibly have reached a plateau, and only one field is increasing.

The production curves of the three biggest fields, namely Soma, Tuncbilek, and Seyitomer are shown in Figs. 3–5. The production in the Soma field began in 1940, long before TKI was established (Fig. 3). During the period between 1940 and 1957, the majority of production was from underground mines, constituting 95.5% (4.95 million tons) of 5.18 million tons of cumulative production. Thereafter, surface production increased gradually from 59,300 t in 1957 to an all-time high of 7.41 million tons in 2000, when total production peaked at 7.61

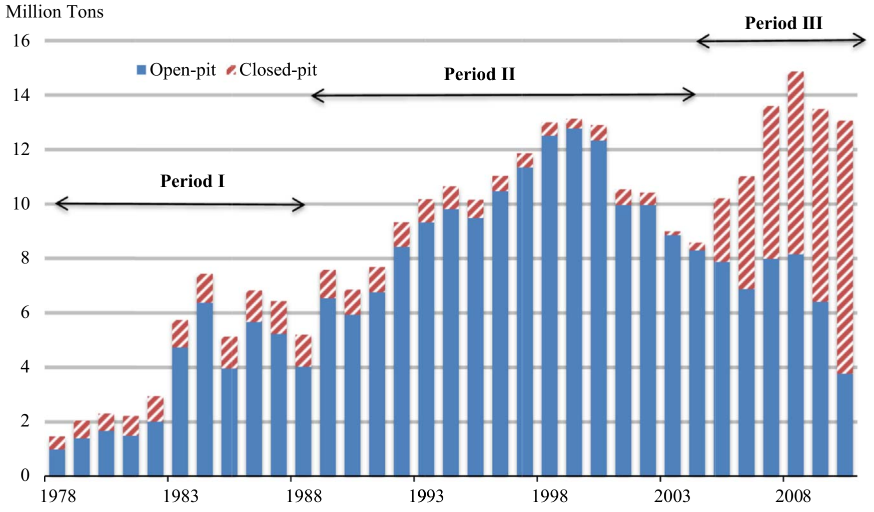

Fig. 2. ELI's open-pit and underground lignite production, 1978–2010.

Table 2
Active TKI lignite fields, end of 2010.

Name of the field	Year of becoming active	Peak production		Average annual Production (Million Tons)	Cumulative production (Million Tons)	Remaining reserves (Million Tons)	Production phase
		Date	Quantity (Million Tons)				
Soma	1957	2000	7.61	2.61	154.41	43.98	Definite Declining Phase (DDP)
Ilgin	1979	1987	0.64	0.37	11.82	18.53	
Orhaneli	1980	1998	1.44	0.54	16.77	31.37	
Denis	1981	1999	3.54	1.90	57.09	160.19	
Tınaz-Bagyaka	1985	1997	3.30	1.24	32.31	25.29	
Tuncbilek	1957	1985	6.53	3.59	193.67	272.41	Hard to define / Plateau Phase
Seyitomer	1960	2009	8.64	4.60	234.81	147.42	
Keles	1979	2009	0.40	0.18	5.83	43.75	
Can	1979	2009	2.52	0.79	25.18	78.82	
Yatagan-Eskihisar	1979	1985	4.13	2.52	80.73	36.65	
Milas	1979	2008	8.62	4.07	130.26	262.37	
Eynez	1980	2010	10.48	2.07	64.03	360.99	Definite Build-Up / Increase Phase

Note: The fields marked with (¶) are ones where production began before TKI was established; for convenience we only consider production after 1957.

million tons. Within the same period, the underground production continued in a slightly decreasing pattern until it completely stopped in 2004. After 2000, total production declined to 1.97 million tons in 2010, which was all from surface mines. The cumulative production of this field from 1940 to 2010 was 185.21 million tons of which 83.5% was from surface and 16.5% was from underground mines and at present it is clearly in decline.

The Tuncbilek field, also in operation since 1940, has been in plateau phase for some time (Fig. 4). Similar to the Soma field, its lignite production was mainly from underground mines, constituting 74.4% of cumulative production before 1957, which was 5.66 million tons. After 1957, however, surface production dominated with a share of 77.67% of cumulative production, which is 249.35 million tons. The total annual production rose from 53,835 t in 1940 to 1.27 million tons in 1957 and further to a higher rate of 2.96 million tons in 1974. During the subsequent period, production continued fairly steadily, showing cyclical behavior to reach a high in 2008 with 7 million tons.

The Seyitomer field, which began operating in 1960, is the largest field in terms of cumulative production since the establishment of TKI (Fig. 5). This field is distinct from the Soma and Tuncbilek fields due to the fact that its production is only from surface mines. The annual production in the field rose nearly exponentially from 40,719 t in 1960 to a local peak value of 4.71 million tons in 1978. Thereafter, it has fluctuated with peaks in 1992, 1999, and 2009. Its highest production came in 2009 with a value of 8.64 million tons.

4. Production forecasting

According to Table 2 in which the fields are grouped based on their production phases, Soma, Ilgin, Orhaneli, Denis, and Tinaz-Bagyaka are in Definitely Declining Phase (DDP). The productions of the fields in this group have already passed their historic peaks. Only the Eynez field can be defined as in a Definitely Increasing Phase (DIP) and the future production of other fields is hard to define based on the past production data because of their Plateau Phase (PP).

The future productions of PP fields are estimated by using Hubbert's rate-of-production curves, as explained in Section 2.4. According to the Hubbert curves shown in Figs. 6 and 7, the Tuncbilek and Seyitomer fields show significant probabilities for entering into a DDP in the near future. The estimated rate-of-production peaks occurred in 2008–2009 in Tuncbilek and in 2002–2003 in Seyitomer. For the past two years, both fields are actually in decline.

The historic development of shares of 5 DDP fields in annual production is examined together with those of Tuncbilek and Seyitomer, which are the two most important PP group fields, in Fig. 8. While DDP fields have been responsible for an average of 22% of the annual production of TKI, the annual average share of Tuncbilek and Seyitomer (T+S) was 51.72% during the period between 1957 and 2010. The DDP curve has been in an obvious decline since 1997 and T+S curve in PP since 1986. The combined curve of these, however, is in

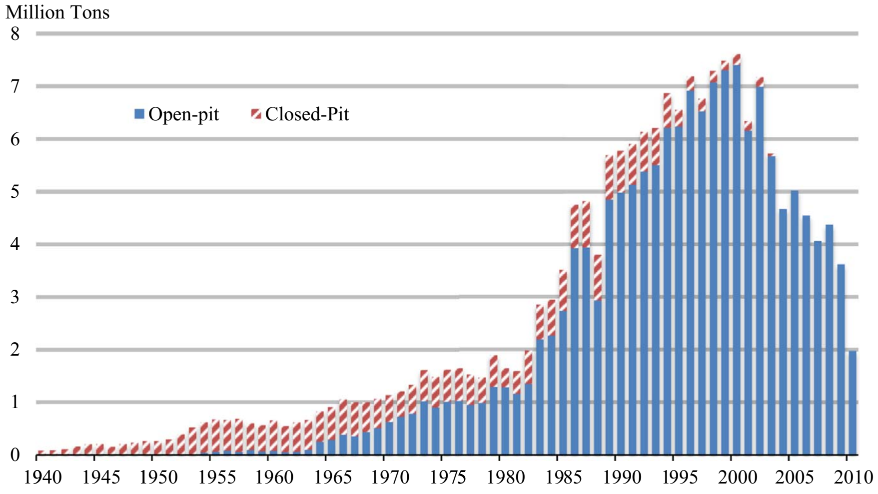

Fig. 3. Lignite production in the Soma Field, 1940–2010.

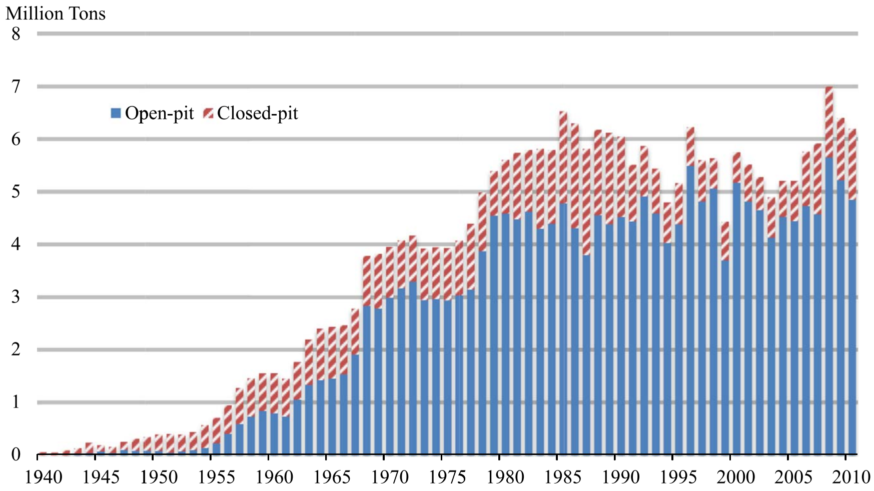

Fig. 4. Lignite production in the Tuncbilek Field, 1940–2010.

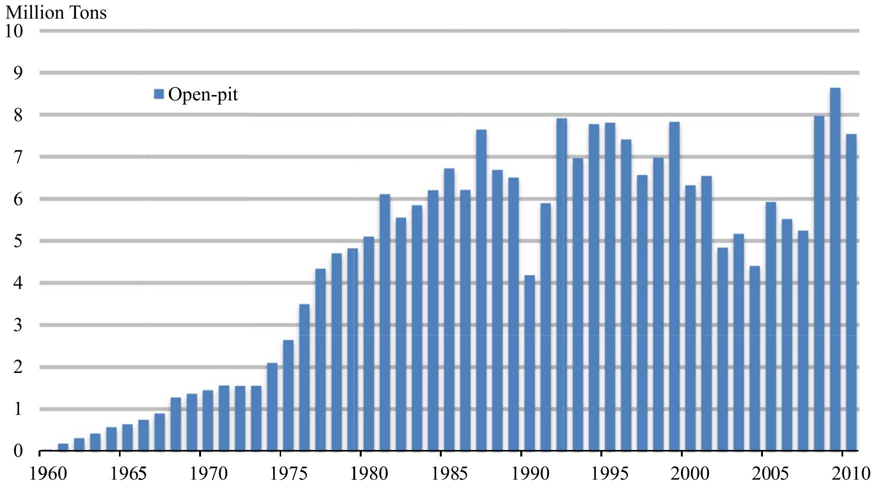

Fig. 5. Lignite production in the Seyitomer Field, 1960–2010.

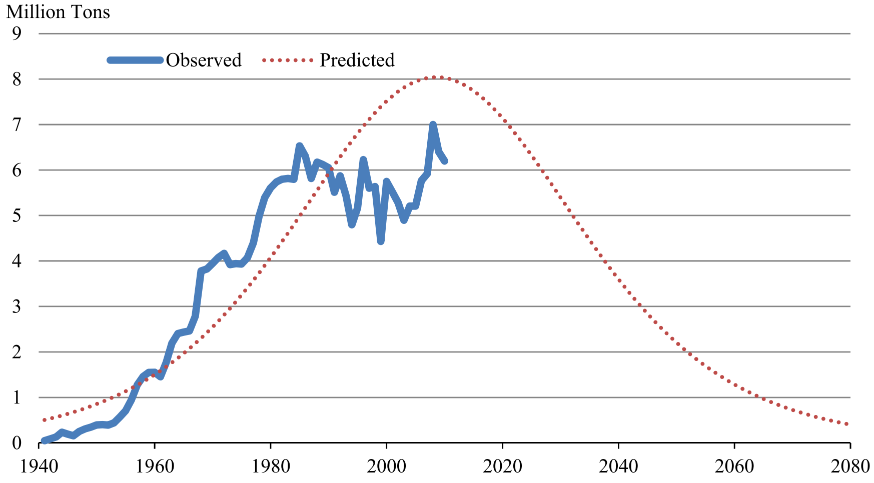

Fig. 6. Tuncbilek Hubbert curve.

a declining phase since 1996, indicating that these seven fields, which usually produce more than half of TKI's production, would be decisive in TKI's future lignite supply.

Finally, the exponential decline curve (Arps, 1945; Höök et al., 2009) and depletion rate curve (Höök, 2009) methodology were applied to the best examples of DDP (Soma) and PP (Tuncbilek) fields in order to predict prospective production and historical depletion. The decline curve analysis was successful in capturing the declining trend of the Soma field production (Fig. 9). It suggests a decline rate of 12.5% after peak production occurred in 2000 with 7.61 million tons. The decline curve estimated a cumulative production of 48.40 million tons during the period between 2000 and 2010, while actual cumulative production was 55.12 million tons for the same period. This excess production would lead to a more rapid decline rate in upcoming years.

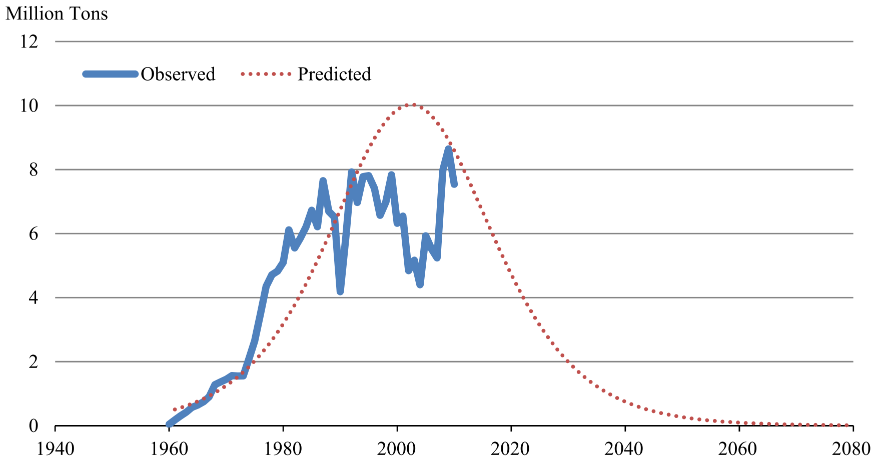

Fig. 7. Seyitomer Hubbert curve.

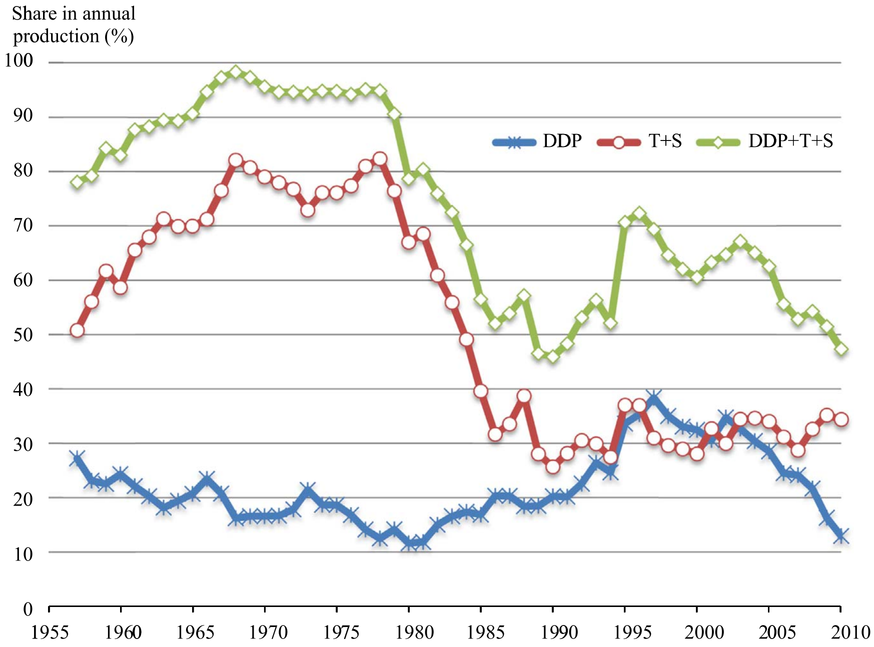

Fig. 8. Contribution of fields in declining phase to TKI's total lignite production. *Note:* DDP (Definite Declining Phase) is the first group in Table 2, T+S is Tuncbilek plus Seyitomer.

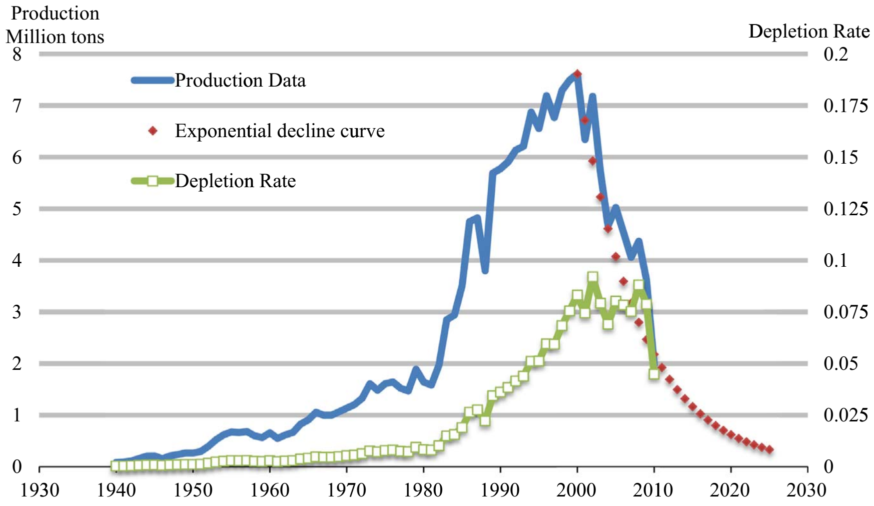

Fig. 9. Soma exponential decline curve and depletion rate analysis.

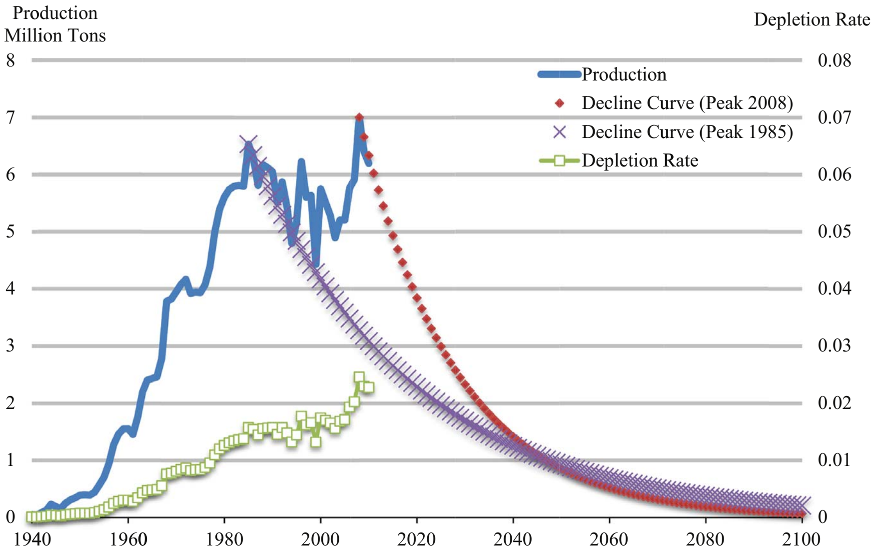

Fig. 10. Tuncbilek exponential decline curve and depletion rate analysis.

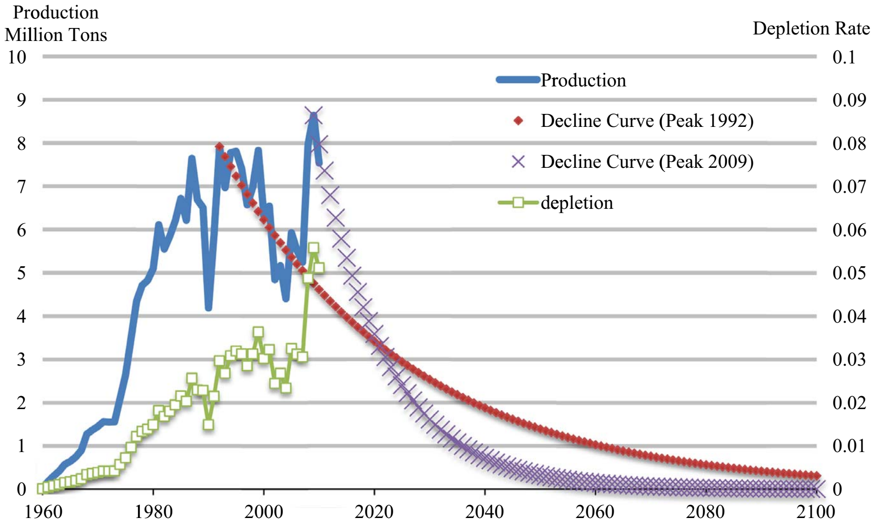

Fig. 11. Seyitomer exponential decline curve and depletion rate analysis.

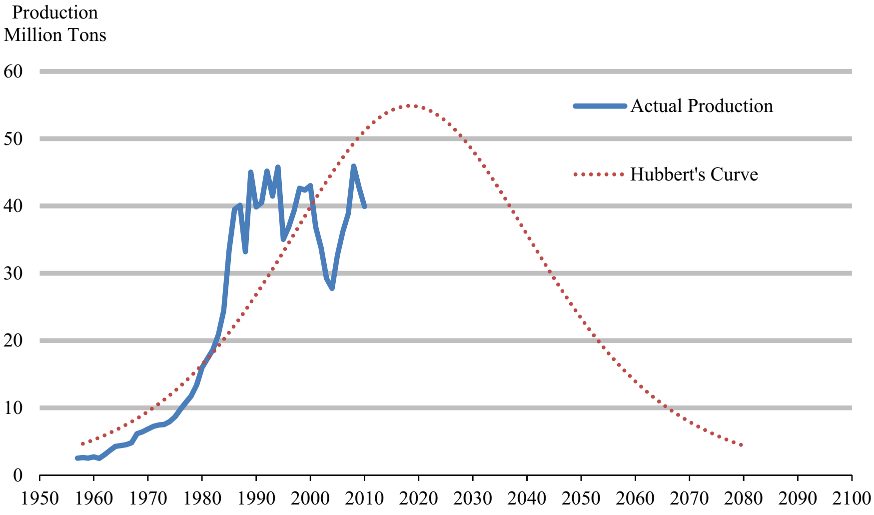

Fig. 12. TKI's actual production and Hubbert's curve estimation, 1957–2010.

On the other hand, the depletion rate analysis suggests that in the field the average annual depletion rate increased exponentially to 8.3% until the actual production peak of 2000, yet it reached the historical highest value of 9.2% with 2 years lag in 2002.

The application of the same methodology to Tuncbilek was rather difficult because it has yet to reach its peak (Fig. 10). Therefore, we used the Hubbert curve peak instead. There was a peak in production from Tuncbilek field in 1985 with a value of 6.53 million tons, yet it later reached its global production peak in 2008 with 7 million tons. If the peak of 1985 (6.53 million tons) is used, the decline curve suggests a production decline rate of 3% and in the case of the peak of 2000 (7 million tons) a constant decline rate of 5%. Similarly, if the peak of 1992 (7.92 million tons) is used, the decline curve suggests a production decline rate of 8% and in the case of the peak of 2009 (8.64 million tons) a constant decline rate of 3%.

The same analyses for the Seyitomer field (Fig. 11) reveal two peaks, namely 1992 (7.92 million tons) and 2009 (8.64 million tons). While the first peak based decline curve analysis points to an 8% constant rate, if the global peak is understood to be the latter one, the decline rate would amount to only 3%. These results are important for the future production of TKI since the Seyitomer field together with Tuncbilek were responsible for 34.39% of the company's production in 2010.

As can be seen in the Hubbert, exponential decline, and depletion rate curve analyses explained above, most of the fields, especially the largest ones, in addition to the DDP fields, tend toward decline. Since these fields constitute the largest shares in overall production, it can be concluded that the overall production of TKI will decrease in the coming future.

This conclusion was also supported by the Hubbert curve of TKI's overall production (Fig. 12). The curve predicts a peak of 54.87 million tons in 2018 and the same production level of the 1960s in 2080. This estimate can be considered to be reasonable although significant gaps exist between the Hubbert curve and actualization since "over-production" during the period 1985–2001[6] was compensated for by "under-production" during the post-2001 period.

As mentioned above, the cumulative lignite production of TKI between 1957 and 2010 was 1245 million tons. The Hubbert curve estimated a cumulative production of 1240 million tons for the same period. The Ultimate Recoverable Resource (URR) given as the area under the Hubbert curve corresponds to the summation of the cumulative production of 1.24 billion tons and remaining recoverable reserve of 2.24 billion tons (TKI, 2012).

5. Conclusions

We examined TKI's production from a historical perspective. Afterwards, we made forecasts of future production using Hubbert's methodology along with depletion rate and decline curve analyses. According to the forecast analyses, most of the largest lignite fields of the company have a tendency to enter a declining phase of production in the near future. Since these fields constitute the largest shares in overall production, it can be concluded that the overall production of TKI will be in a decreasing trend in the coming future. This conclusion was also supported by the Hubbert curve of TKI's overall production. The curve predicts a peak of 54.87 million tons in 2018 and the same production level of the 1960s in 2080. This conclusion was made based on analyses covering the data until 2010, however, recent developments in the privatization of some major fields such as Seyitomer, Milas, Yatagan and Tınaz-Bagyaka in 2012 and 2013 should also be considered in further studies.

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[6] While the actual cumulative production in this period was 680.18 million tons, the Hubbert curve predicted a cumulative 523.77 million tons.

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