U.S. EPA Coalbed Methane Outreach Program

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Pre-feasibility Study for Coal Mine Methane Drainage and Utilization at the Kozlu Coal Mine in Zonguldak, Turkey

U.S. Environmental Protection Agency
March 2015

Pre-feasibility Study for Coal Mine Methane Drainage and Utilization at the Kozlu Coal Mine in Zonguldak, Turkey

Sponsored by:
U.S. Environmental Protection Agency, Washington, DC USA

Prepared by:
Eastern Research Group
HEL-East Ltd.
Ruby Canyon Engineering Inc.

March 2015

Acknowledgements

This report was prepared by Eastern Research Group (ERG) at the request of the United States Environmental Protection Agency (USEPA), in support of the Global Methane Initiative (GMI). In collaboration with the Coalbed Methane Outreach Program (CMOP), the principal authors of the report are Ronald Collings and Michael Cote with Ruby Canyon Engineering (RCE); Neil Butler with Harworth East Limited (HEL); Brian Guzzone and Brooke Leigh Robel with Eastern Research Group (ERG); Dr. Abdullah Fisne with Istanbul Technical University; C. Ozgen Karacan with National Institute for Occupational Safety and Health; and Dr. Satya Harpalani with Southern Illinois University.

Disclaimer

This report was prepared for USEPA. This analysis uses publicly available information in combination with information obtained through direct contact with mine personnel, equipment vendors, and project developers. USEPA does not:

(a) make any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any apparatus, method, or process disclosed in this report may not infringe upon privately owned rights;

(b) assume any liability with respect to the use of, or damages resulting from the use of, any information, apparatus, method, or process disclosed in this report; or

(c) imply endorsement of any technology supplier, product, or process mentioned in this report.

Table of Contents

Acronyms and Abbreviations

Btu	British thermal unit
C	Celsius
Bcm	Billion cubic meters
CAPEX	capital expenditure
CBM	coalbed methane
CER	Certified Emission Reduction
CH_4	methane
CMM	coal mine methane
CMOP	Coalbed Methane Outreach Program
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
GHG	greenhouse gas
GMI	Global Methane Initiative
IRR	internal rate of return
kcal	kilocalorie
kg	kilogram
km	kilometer
M	million
m^3	cubic meter
Mcf	million cubic feet
MJ/m^3	million joules per cubic meter
mm	millimeter
Mt	million tonnes
MW	megawatt
MWe	megawatt electrical power
MWhr	megawatt hour
MWth	megawatt thermal power
NPV	net present value
t	tonne
tCO_2e	metric tons of carbon dioxide equivalent
tonne	metric ton
VAM	ventilation air methane
VER	verified emission reduction

Tables and Figures

1.0 Executive Summary

As part of its commitment to support the Global Methane Initiative (GMI), the U.S. Environmental Protection Agency's (USEPA's) Coalbed Methane Outreach Program (CMOP) commissioned a pre-feasibility study to examine the potential for a coal mine methane (CMM) recovery and utilization project at the Kozlu underground coal mine in Zonguldak, Turkey. GMI is a voluntary, multilateral partnership that aims to reduce global methane (CH_4) emissions and to advance the abatement, recovery, and use of methane as a valuable clean energy source. GMI achieves its goals by creating an international network of partner governments, private sector members, development banks, universities, and non-governmental organizations in order to build capacity, develop strategies and markets, and remove barriers to project development for methane reduction, including CMM in Partner Countries. Turkey joined the Initiative in 2010 to improve mine safety to prevent explosions and to recover and use methane from coal mines. More information about Turkey's coal mining sector can be found at https://www.globalmethane.org/documents/toolsres_coal_overview_ch33.pdf as well as https://www.globalmethane.org/documents/coal_cap_turkey.pdf. More information about GMI and coal sector activities can be found at www.globalmethane.org.

Turkey's coal mining industry is dominated by two state-owned companies: Turkish Coal Enterprises (TKI) and Turkish Hardcoal Enterprises (TTK). TKI mines the country's estimated reserves of 11.6 billion tonnes of low quality lignite coals while TTK mines the estimated reserves of 1.3 billion tonnes of bituminous, coking, and non-coking coal in five active mines.

Turkey's hard coal resource is restricted to a relatively small area along its northwest coast of the Black Sea. The coal measures are composed of numerous seams with high gas content. Mining conditions are extremely difficult because of intense faulting and folding of the strata with inclinations of up to 90 degrees. The Zonguldak coal basin contains Upper Carboniferous bituminous coal, including the Kozlu formation. There are more than 20 coal seams within the Kozlu formation. Net coal thickness for this stratigraphic sequence ranges from 30 to 32 meters across the Kozlu region. The calorific value for coals in the basin range from 6,200 to 7,250 kilocalories per kilogram of coal (kcal/kg).

The strata have been tectonically disturbed, resulting in significant faulting and folding. The mined seams can have a dip from 0 degrees to 90 degrees, making mining conditions very difficult and precluding the use of mechanized coal mining equipment. Instead, labor intensive methods are in use. The coal is also prone to spontaneous combustion, adding to the already difficult mining conditions imposed by the structural complexity of the geology.

Kozlu is one of the deepest mines at about -500 meters and significant reserves remain for many decades of coal production, with the possibility of mining below -1000 meters in the future. TTK management expects the trend of mining deeper levels will continue. Under current practices, the number and severity of outbursts will increase as will methane emissions at the coal face as mining at deeper levels occur. Although coal production is declining, infrastructure projects including gallery and deep shaft development are underway with the goal of increasing production to 5 million tonnes per year from TTK's five mines.

In-situ gas content has been measured at all of the TTK mines. The Kozlu mine is among the deepest and has correspondingly higher measured and specific emissions: approximate average gas content of 9.07 cubic meters per tonne (m^3/tonne), average specific emissions of 20.94 m^3/tonne mined.

Two of the five active TTK mines—Karadon and Kozlu—have severe coal outburst problems that disrupt mining and cause injury or death to miners. TTK management determined that control of the coal outburst problems is a top priority.

Current practices at the Kozlu coal mine to control outbursts have proven inadequate. There is no gas drainage system in place (i.e., vented in the mine workings); the design of the outburst control system is insufficient because the drill cannot reach the end of the heading development; and the drilling equipment cannot drill far enough ahead to enable outbursts to be located, discharged, and drained (current limit is 25 meters). The limited reach of the drilling equipment means that outburst control techniques and corresponding management processes will continue to be ineffective.

Based on the meeting with TTK in September 2013, and a preliminary analysis of the information gathered during the site visit and thereafter, the Kozlu coal mine was selected for this pre-feasibility study (e.g., TTK's gassiest mine, opportunities for controlling outbursts). The pre-feasibility study focuses on developing recommendations to reduce methane gas outbursts in the Kozlu mine and evaluating the potential to capture methane for utilization.

1.1 Observations and Recommendations

The study finds that before a methane capture and utilization project is considered, coal outburst control should be prioritized and additional information should be gathered and analyzed to reduce uncertainty and provide a sound basis for investment. After making improvements to control coal outbursts, the mine should be further evaluated to determine specific opportunities for CMM recovery and use (see Section 8.0 for initial potential end use options).

To prevent frequent outbursts and resulting injuries or fatalities at Kozlu, the following approach for improving safety and operations within the mine is recommended (see Section 6.0 for additional details):

- Generate a budget for improved equipment and procedures for outburst control.
- Procure new lightweight powerful in-mine drilling rigs with high quality rods and bits that have the capacity to drill 60 to 100 meters and train personnel on usage of the equipment.
- Design and install a new methane drainage pipework system in the mine capable of extracting gas/dust away from the drill hole and then away to the outside of the mine.
- Install a new methane extraction plant (a suitable vacuum pumping station design is available).
- Develop a new outburst control design and implementation protocol (incorporating the new drilling system and training for operators, methane drainage pipework, and methane extraction plant).

- Develop new outburst management processes that correspond to the new equipment and drainage design and procedures.
- Once these outburst control recommendations are established, drainage volumes and gas quality should be monitored to determine the feasibility of establishing a technically and economically feasible end use technology for the mine methane.

Budget costs for recommendation #2 (procuring new drilling equipment) are expected to be approximately USD$300,000 for the Kozlu mine. After demonstrating that the drilling equipment performs as recommended, it would then be appropriate (in a staged sequence) to install underground pipes. The cost of the underground pipes is entirely dependent on distance to mine shaft and pipe diameter/material, but the cost would be in the range of $100,000 to $500,000. Once the pipework is installed and the gas is discharged on the surface, a methane extraction plant should be installed (estimated cost $350,000). The total budget for implementing the recommendations for the Kozlu mine, including external drainage design consultants and all equipment, training, and on the job practical instruction, would be approximately $1 million phased in over the course of two years.

Although the Kozlu mine is gassy, factors such as low gas permeability, the fractured nature of the coal geology, and the low, non-mechanized production rates mean that CMM pre- or post-drainage techniques for methane capture during production are likely to be unsuccessful (distinctly separate from outburst control). At this time, outburst control should be a primary priority for TTK.

In the first phase of improved outburst control, the outbursts of gas will be encountered intermittently, and there will not be continuous CMM gas flow available which would be suitable for utilization. With the establishment of the improved drilling, gas gathering and extraction pump systems in place to capture and safely remove the outburst gas, drainage volumes and gas quality can be monitored to determine the feasibility of establishing a profitable end use technology for the mine methane.

Several CMM capture and utilization options were evaluated for this study. At this time, because of the intermittent drainage gas flow, the only technically and commercially viable option for methane utilization is VAM to power, using regenerative thermal oxidizers (RTO) coupled to waste heat recovery boilers and a steam turbine. The average methane concentration at the main mine ventilation shaft is >0.6 percent methane; therefore, there is sufficient heat energy in the gas to maintain self-sustaining operation of the RTOs and deliver excess heat via the hot gas bypasses (from each RTO) into a boiler and then to a superheater connected to an impulse steam turbine. Typical net cycle efficiency is in the range of 18 to 28 percent, depending on design of the RTO, boiler, and steam turbine. Steam turbine manufacturing period is in the 9 to 12 month range, therefore the project would have a 12 to 14 month implementation period. It would also be possible to explore the use of RTOs interconnected to an Organic Rankine Cycle generator or a Rotary Screw generator. These technologies are lower efficiency at around 15 percent net cycle efficiency.

To develop this project, the high capital investment would demand a long term power purchase agreement from the coal mine to buy the electricity, and possibly revenue from carbon credits.

2.0 Background

As part of its commitment to support the Global Methane Initiative (GMI), the U.S. Environmental Protection Agency's (USEPA's) Coalbed Methane Outreach Program (CMOP) commissioned a pre-feasibility study to examine the potential for a coal mine methane (CMM) recovery and utilization project at Kozlu coal mine in Zonguldak, Turkey. GMI is a voluntary, multilateral partnership that aims to reduce global methane (CH_4) emissions and to advance the abatement, recovery, and use of methane as a valuable clean energy source. GMI achieves its goals by creating an international network of partner governments, private sector members, development banks, universities, and non-governmental organizations in order to build capacity, develop strategies and markets, and remove barriers to project development for methane reduction, including CMM in Partner Countries. Turkey joined the Initiative in 2010 to improve mine safety to prevent explosions and to recover and use methane from coal mines. More information about Turkey's coal mining sector can be found at https://www.globalmethane.org/documents/toolsres_coal_overview_ch33.pdf as well as https://www.globalmethane.org/documents/coal_cap_turkey.pdf. More information about GMI and coal sector activities can be found at www.globalmethane.org.

Turkey's hard coal resource is restricted to a relatively small area along its northwest coast of the Black Sea. The coal measures are composed of numerous seams with high gas content. Mining conditions are extremely difficult because of intense faulting and folding of the strata with inclinations of up to 90 degrees. Turkey's coal mining industry is dominated by two state-owned companies: Turkish Coal Enterprises (TKI) and Turkish Hardcoal Enterprises (TTK).

TKI mines the country's estimated reserves of 11.6 billion tonnes of low-quality lignite coals (approximately 2.5 billion tonnes) while TTK mines the estimated reserves of 1.3 billion tonnes of bituminous, coking, and non-coking coal in five active mines in the Zonguldak basin. **Figure 1** shows the location of Turkey's coal resource areas. While there are some methane emission problems in TKI mines, they are unusual in that the source does not appear to come from the lignite itself, which has very low native methane content, but from other as yet indeterminate sources. This issue is currently being addressed by a Turkish administered public-private partnership to determine the gas source and to drain and utilize the gas so that mine safety is maintained. In contrast, the carboniferous age bituminous coals of the TTK mines have numerous seams of high gas content but low permeability coal. Two of the five active TTK mines—Karadon and Kozlu—have documented severe coal outburst problems that disrupt mining and have caused injuries and deaths.

Following initial communication with TTK management, the project team visited Zonguldak on Turkey's northwest coast in September 2013. As shown in **Figure 2**, Zonguldak is the location of TTK's headquarters and their five active mines. Of the five TTK-operated mines, the Kozlu and Karadon mines are of the greatest concern to TTK because they are the gassiest underground mines and have the greatest number of gas outbursts. While TTK has targeted and attempted to drain high pressure gas buildup prior to mining, their efforts to date have not been successful. **Figure 3** shows the location of the Kozlu mine and ventilation shaft.

Figure 1: Location of Turkey's coal resources by type[1]

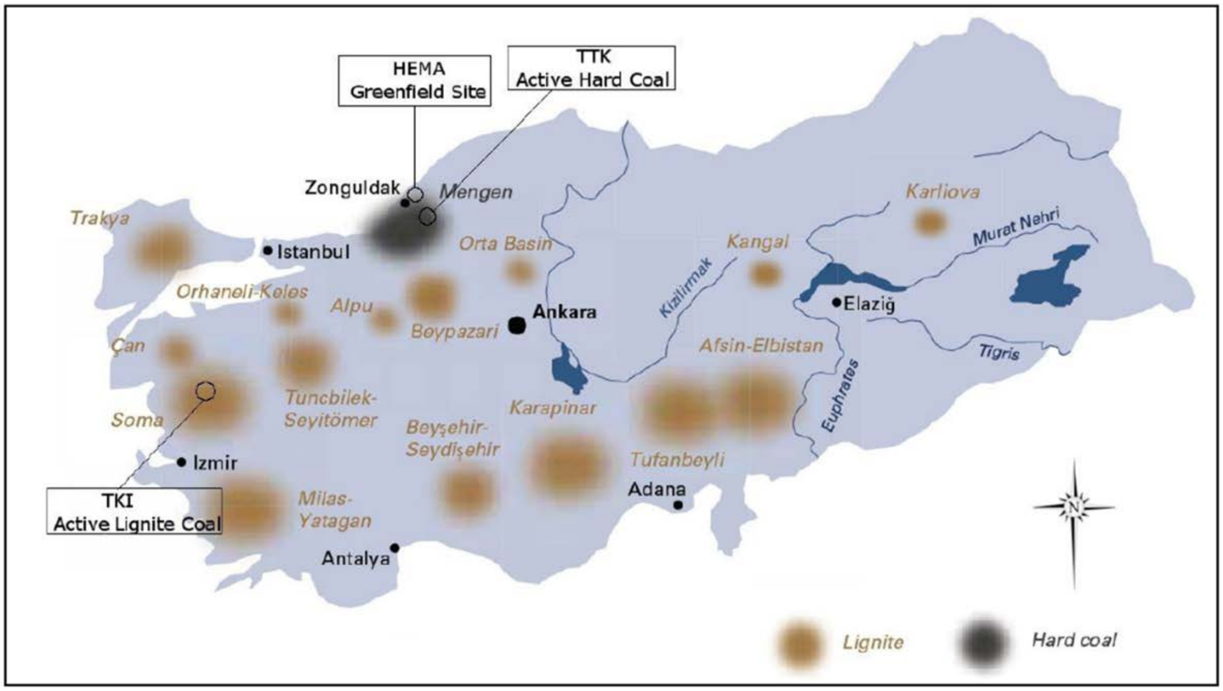
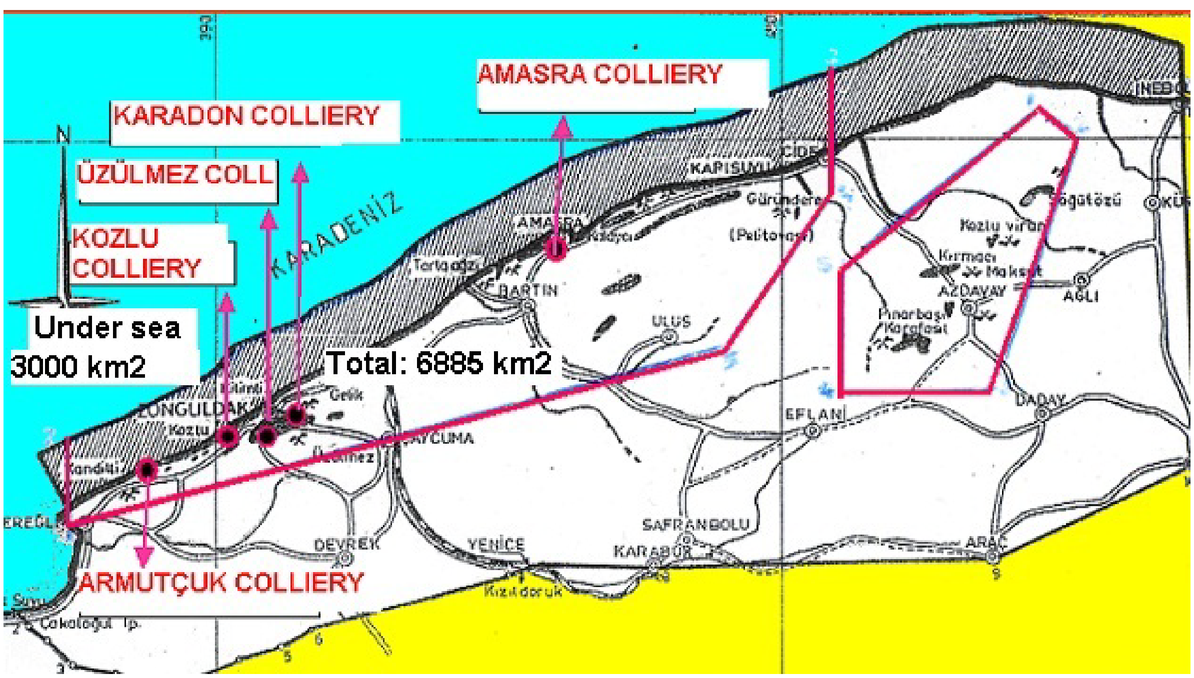


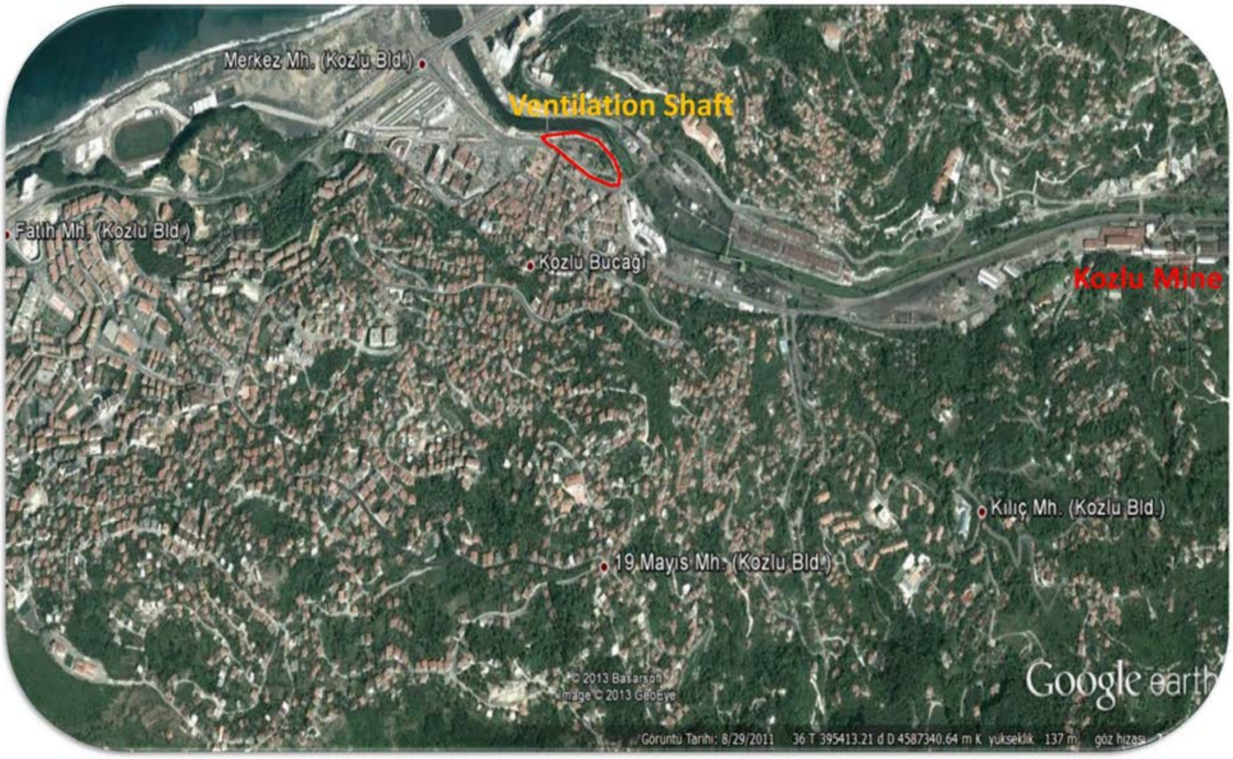
Figure 2: Location of the TTK coal concession, active mines, and city of Zonguldak[2]



1 Virginia Polytechnic Institute and State University (Virginia Tech) Virginia Center for Coal & Energy Research (2012)

2 Okten et al (2011)

Figure 3: Location of the Kozlu mine and ventilation shaft[3]



There is no pre- or post-mining drainage system currently in place at either mine (i.e., gas is vented in the mine workings).

Kozlu is the gassiest in terms of gas content and emissions per tonne of coal mined. The mine produces approximately 2,000 tonnes per day of coal and exhausts approximately 1.83 billion cubic feet per day (Bcf/d) or 51,826 m^3/day of methane using two exhaust fans. Typical concentration of methane at the main mine ventilation shaft is >0.6% methane.

Based on the meeting with TTK in September 2013, and a preliminary analysis of the information gathered during the site visit and thereafter, the Kozlu coal mine was selected for this pre-feasibility study (e.g., TTK's gassiest mine, opportunities for controlling outbursts). The study focuses on developing recommendations to reduce methane gas outbursts in the Kozlu mine and evaluating the potential to capture methane for utilization.

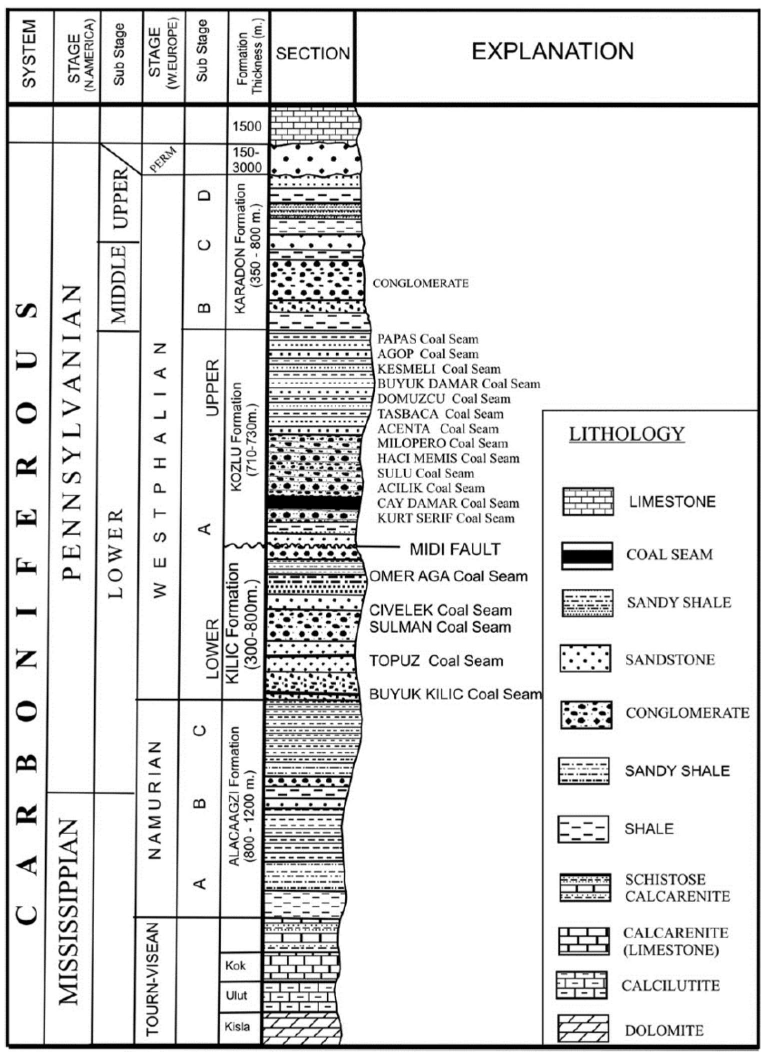
[3] Virginia Polytechnic Institute and State University (Virginia Tech) Virginia Center for Coal & Energy Research (2012)

3.0 Summary of Mine Characteristics

3.1 Geologic Setting

The Zonguldak coal basin contains Upper Carboniferous bituminous coal. The coal is located within a deltaic sedimentary sequence of Westphalian-A age. The coal-bearing sequence of Zonguldak basin contains the Namurien Alacaağzı Formation, Westphalian A Kozlu Formation, and Westphalian B-D Karadon Formation. Westphalian-A aged Kozlu Formation is formed by interbedded sandstones, siltstones, mudstones, conglomerates, and coals. The overlying Westphalian B-D aged Karadon Formation has a similar succession as the Kozlu formation, but has fewer coal seams. There are more than 20 coal seams within the Kozlu formation. Net coal thickness for this stratigraphic sequence ranges from 30 to 32 meters across the Kozlu region. **Figure 4** shows a generalized stratigraphic section for Zonguldak Coal Basin.

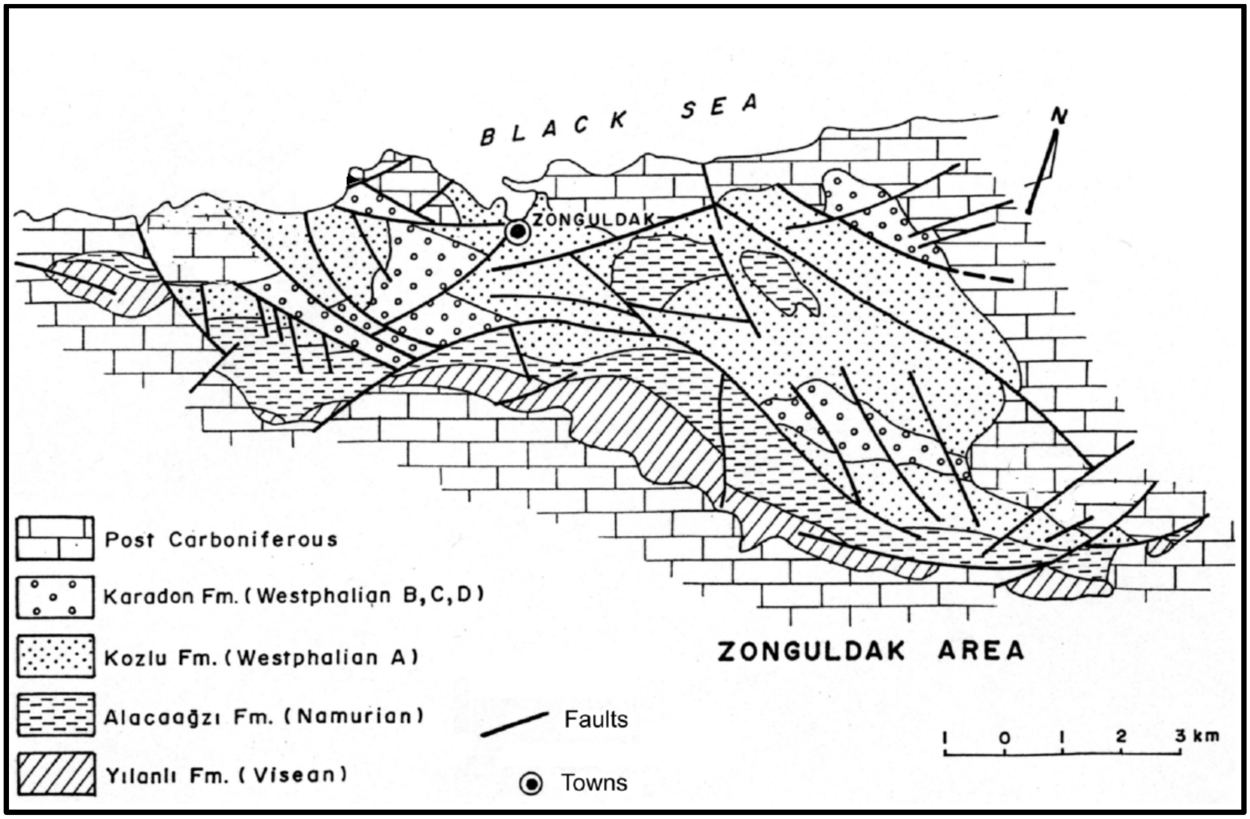
Figure 4: Generalized stratigraphic section of the Zonguldak Coal Basin[4]



4 Toprak, S. (2009)

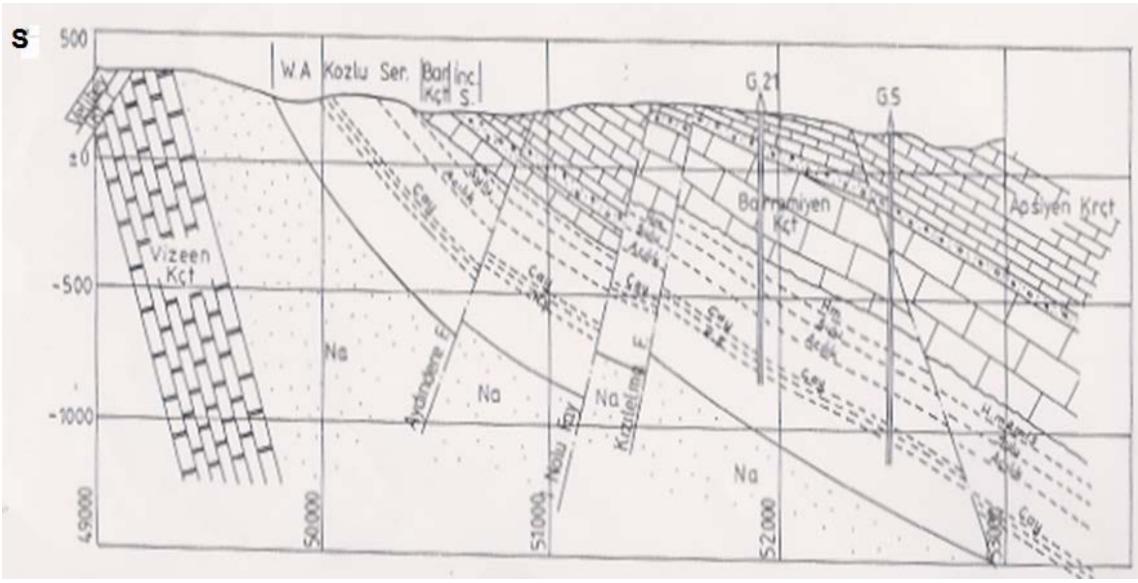
The strata have been tectonically disturbed, resulting in significant faulting and folding. The mined seams can have a dip from 0 degrees to 90 degrees, making mining conditions very difficult and precluding the use of mechanized coal mining equipment. **Figure 5** shows a geological map of the basin and **Figure 6** shows a geologic cross-section.

Figure 5: Geological map of Zonguldak Coal Basin, Turkey[5]



5 Hosgormez, H. (2007)

Figure 6: Diagrammatic geologic structural cross-section of Zonguldak mining area[6]



3.2 Coal Characteristics

The calorific value for coals in the basin range from 6200 to 7250 kcal/kg. **Table 1** shows the coal rank by mine. The coal is also prone to spontaneous combustion, adding to the already difficult mining conditions imposed by the geology's structural complexity.

Table 1: Coal rank by mine[7]

	Colliery			
	Armutçuk	**Amasra**	**Kozlu - Üzülmez**	**Karadon**
ISO Code Number	622	711	533-534	534
ISO Class	VIA	VII	VC – VD	VC
Cokeability	Medium/Weak	Very Weak	Medium/Well	Very Well
ASTM Rank Scale	62-148	58-139	68-154	69-155
ASTM Rank Class	II-Bt	II-Bt	II-Bt	II-Bt
ASTM Rank Group	Hv Ab	Hv Bb	HV Ab	HV Ab

3.3 Coal Production

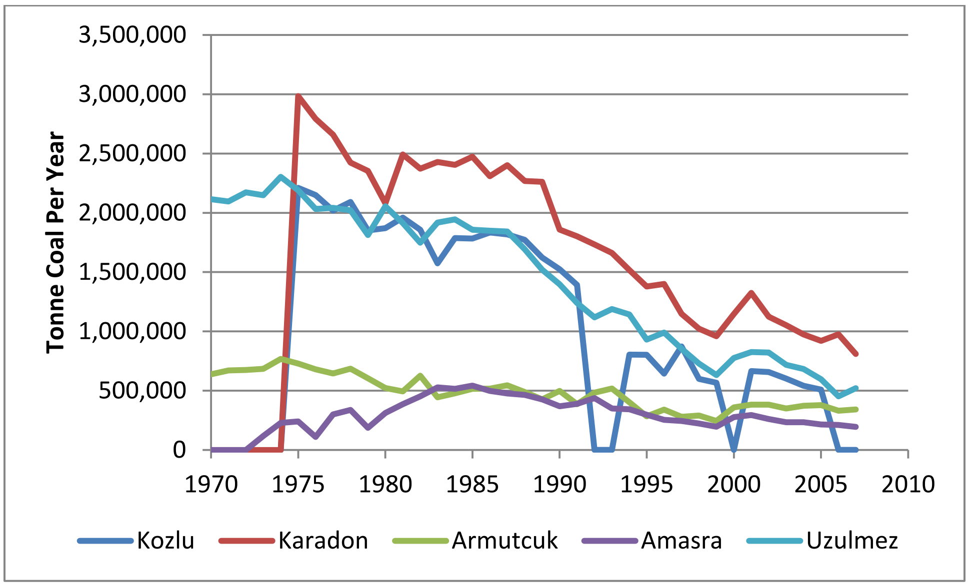
Because of the difficult mining conditions imposed by the geology's structural complexity, mechanized mining methods cannot be used. Instead, labor intensive methods are in use (e.g., retreating short wall

6 Ozturk, M. (2013a)
7 Ozturk, M. (2013b)

method with back caving is common). The high pressure air breaking method is used in the steep coal seams with a dip greater than 45 degrees and a seam thickness greater than two meters. Saleable production is approximately 80% of mine production.

Although coal production is declining, infrastructure projects including gallery and deep shaft development are underway with the goal of increasing production to 5 million tonnes per year from TTK's five mines (**Figure 7**). TTK has also opened approximately 40% of its resources to private sector miners under a royalty agreement. Currently, the private sector companies are producing about 1 million tonnes per year, but are expected to increase production to 5 million tonnes per year in the midterm.

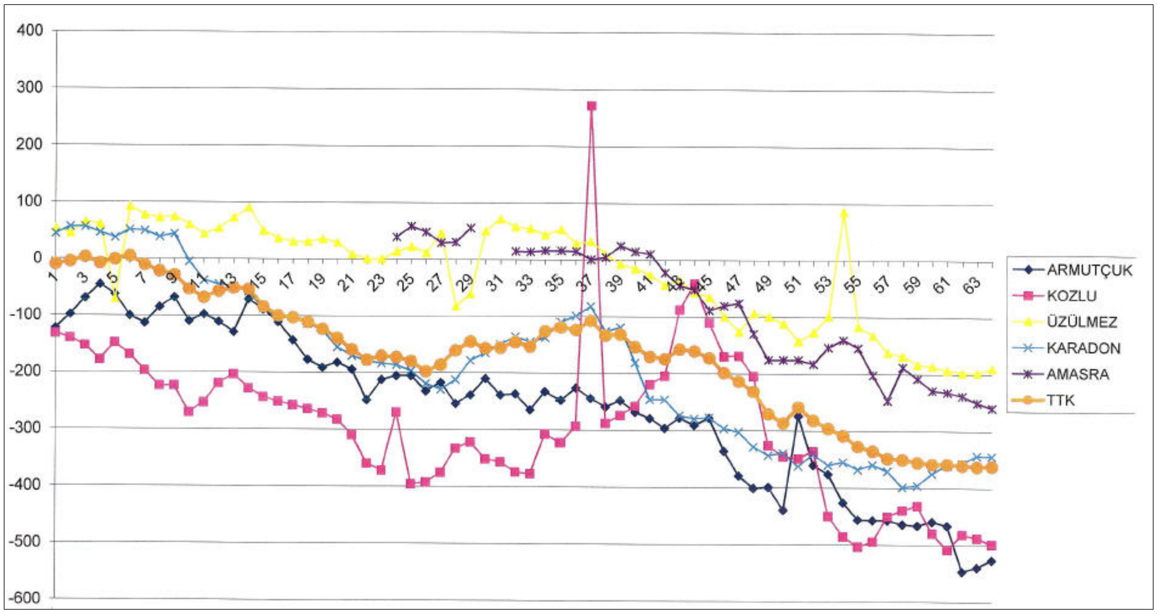
Figure 7: Yearly coal production for TTK mines in Zonguldak coal basin[8]



Depth of mining has increased through time as shown in **Figure 8**. Currently, Armutcuk and Kozlu are the deepest at about -500 meters with Karadon at about -350 meters. At the Kozlu mine, significant reserves remain for many decades of coal production with the possibility of mining below -1000 meters in the future. TTK management expects the trend of mining deeper levels will continue. Under current practices, the number and severity of outbursts will increase as will methane emissions at the coal face as mining at deeper levels occurs.

[8] Ozturk, M. (2013a)

Figure 8: Average depth of mining from 1941 to 2013 in meters from sea level for the TTK mines[9]



3.4 Coal Reserves

Total production by mine—as well as the remaining coal reserves by confidence category—are listed in **Table 2**. Proven (measured) reserves are significant when compared to production over the last 42 years.

Table 2: Coal produced from 1970 through 2012 and remaining reserves by category, million tonnes[10]

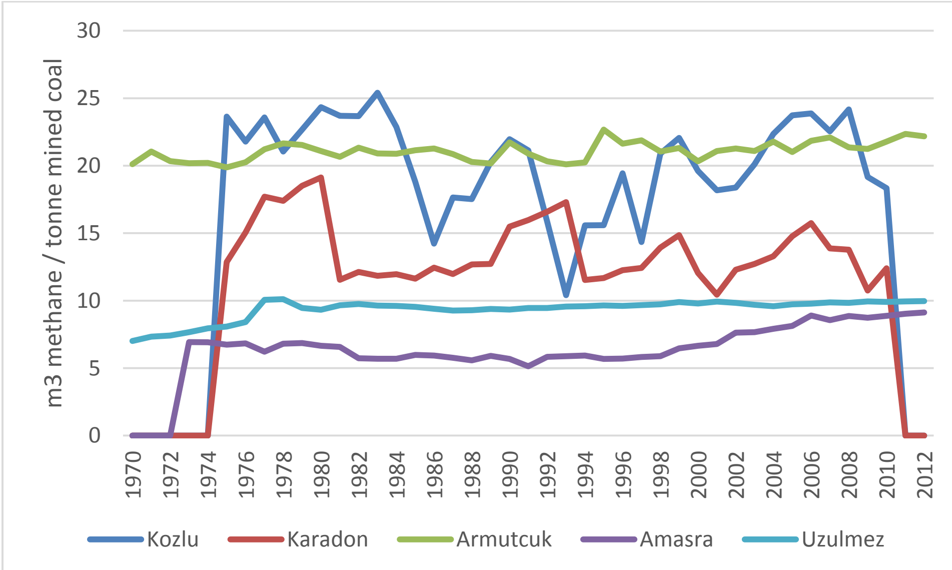
Mines	Produced	Measured	Probable	Possible	Total Reserves
Armutçuk	20	10	16	8	34
Kozlu	38	70	41	48	159
Üzülmez	58	138	94	74	306
Karadon	62	137	159	117	413
Amasra	12	171	115	121	407
TTK total	190	526	425	368	1,319

4.0 Gas Resources Assessment

Methane emissions from TTK mines are reported as specific emissions, expressed in cubic meters of methane per tonne (m^3/tonne) of coal produced. **Figure 9** shows the historical specific emissions by mine.

[9] Ozturk, M. (2013b)
[10] Ozturk, M. (2013a)

Figure 9: Specific emissions by mine from 1970[11]



In-situ gas content has been measured at all of the mines as well. **Table 3** compares the average measured gas content with the specific emissions by mine.

Table 3: Average depth of measured sample, number of samples and comparison of measured gas content and specific emissions[12]

Mines	Average Depth (m)	Number Samples	Average gas content (m^3/tonne)	Average Specific Emissions (m^3/tonne mined)	Specific Emissions / Gas Content
Armutçuk	-444	5	4.65	20.95	4.5
Kozlu	-521	29	9.07	20.94	2.3
Üzülmez	-165	11	3.74	9.12	2.4
Karadon	-391	24	7.96	13.84	1.7
Amasra	-186	7	5.49	6.55	1.2

The specific emissions from an active mine will always be greater than the measured gas content of the mined coals. This is because additional methane is released from coals not mined as well as from other gas-bearing strata that have been disturbed by the mining process.

The Üzülmez and Amasra mines are the shallowest and have the correspondingly lowest measured and specific emissions, while the Karadon and Kozlu mines are among the deepest and have correspondingly higher measured and specific emissions. The Armutçuk mine is an exception because, although it is deep, it has relatively low measured emissions (note the small number of samples), but has high specific emissions.

[11] Ozturk, M. (2013a)
[12] Fisne, A. (2013)

Table 4 shows the potential for power generation at the five mines assuming they produce coal at their historical rate, at their average specific emissions rate, and assuming 25% of the total mine emissions can be captured as gas that is usable in power generation equipment[13]. Because the Kozlu and Karadon mines have both high coal production rates as well as high specific emissions, they are the most likely to be able to drain usable quantities of methane for power generation (See Section 8.0 for utilization options considered for this study).

Table 4: Historical mining rate and specific emissions used to estimate future mine emissions and potential power generation assuming 25% emissions capture at usable quality[14]

Mines	Average Mining Rate (Tonne/yr)	Average Specific Emissions (m^3/tonne)	Methane Emissions Million (m^3/yr)	Potential Power Generation (MWe)
Armutçuk	462,647	20.95	9.69	0.969
Kozlu	1,066,389	20.94	22.33	2.233
Üzülmez	1,340,661	9.12	12.23	1.223
Karadon	1,730,070	13.84	23.95	2.395
Amasra	310,654	6.55	2.04	0.204

5.0 Gas Outburst Characterization at TTK

Coal and gas outbursts are a complex, catastrophic, and unstable phenomena that involve the ejection of large volumes of coal, and are often accompanied by gas, such as methane, carbon dioxide, or a mixture of the two. Based on previously documented studies discussed below, past coal outbursts are common at TTK mines and a serious concern for employee safety. Coal and gas outbursts are prevalent in deep and gassy mines, and where gas drainage is either poor or absent. Shepherd et al (1981) reported on outburst occurrences in Australia, North America, Europe, and Asia, and found that more than 90 percent of significant outbursts have been concentrated in the narrow, strongly-deformed zones along the axes of structures such as asymmetrical anticlines, the hinge zones of recumbent folds, and the intensely deformed zones of strike-slip, thrust, reverse, and normal faults. These narrow deformed zones, whether in mesoscopic or mine-scale geological structures, form the loci for stress and gas concentration. Similar studies in China[15] revealed that outbursts nearly always occurred in long, narrow outburst zones along the intensely deformed zones of strike-slip, reverse, or normal faults, within which coal has been physically altered into cataclastic, granular, or mylonitic microstructures.

The problem results from a combination of the effects of stress, gas content, and physico-mechanical properties of the coal. Aside from the stress regime in the mine, a primary explanation for gas outburst

13 A very successful methane drainage system at a typical hard coal mine can drain up to 70% of the total mine emissions as usable quality gas, with the remaining 30% as low-concentration VAM. However, a more common result of methane drainage system efficiency is approximately 25% of usable quality gas.

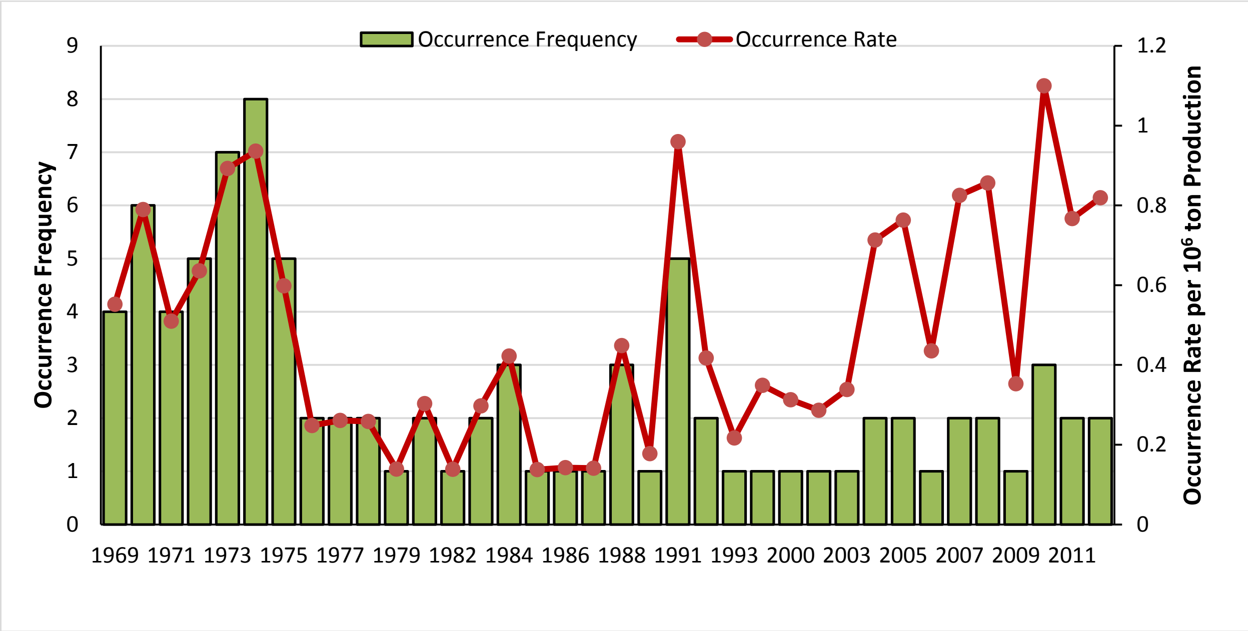
14 Ozturk, M. (2013a)

15 Peng, L.S. (1990)

is the increase in the gas pressure gradient as a mine face approaches a permeability barrier such as a fault zone.

Okten et al (2011) and Fisne & Olgun (2013) have produced assessments of outburst hazards in the Zonguldak coal basin that helps to explain the location and magnitude of various outburst events. **Figure 10** shows the number and frequency of outbursts relative to tonnes of coal mined since 1969 for mines in the Zonguldak basin.

Figure 10: Outburst frequency and occurrence rate relative to tonnes coal mined[16]

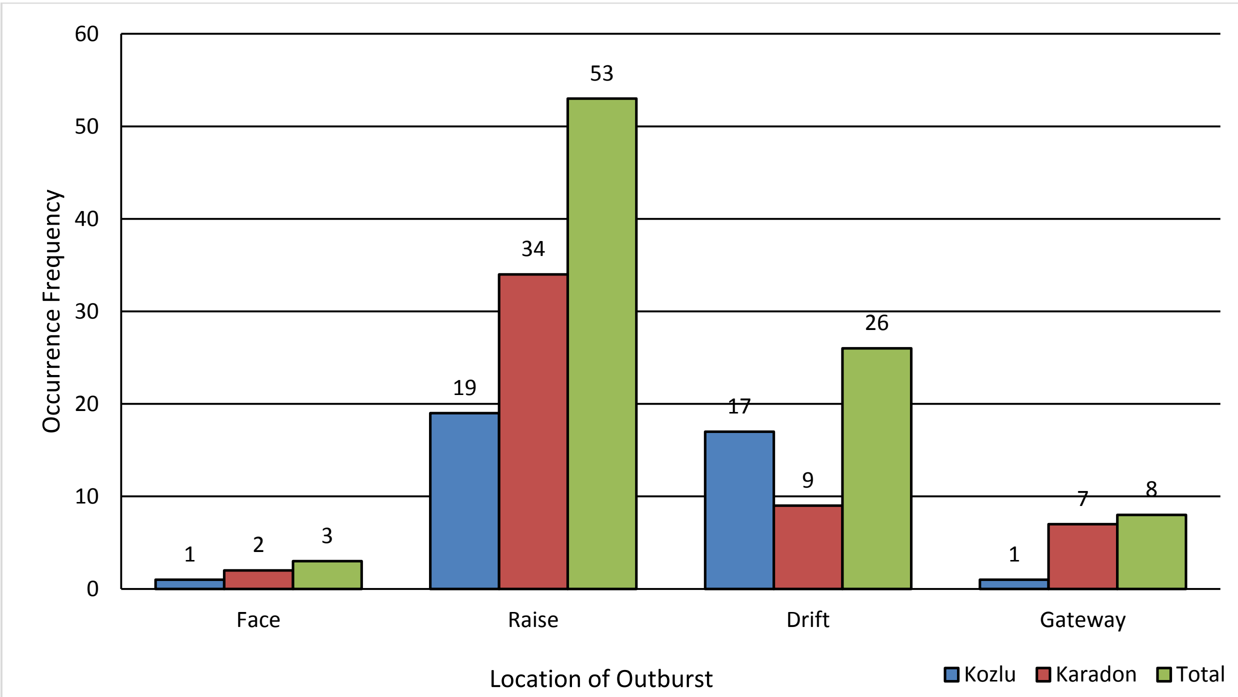


The number of outbursts peaked in 1974 then declined significantly due to implementation of outburst control measures such as inseam drilling for gas drainage and gas detection systems. The increase in the relative rate of outbursts reflects reduced mining rate together with mining at deeper depths.

Okten et al (2011) showed that most outburst occurrences were in the raises and drifts as opposed to the longwall face and gateways, as shown in **Figure 11**.

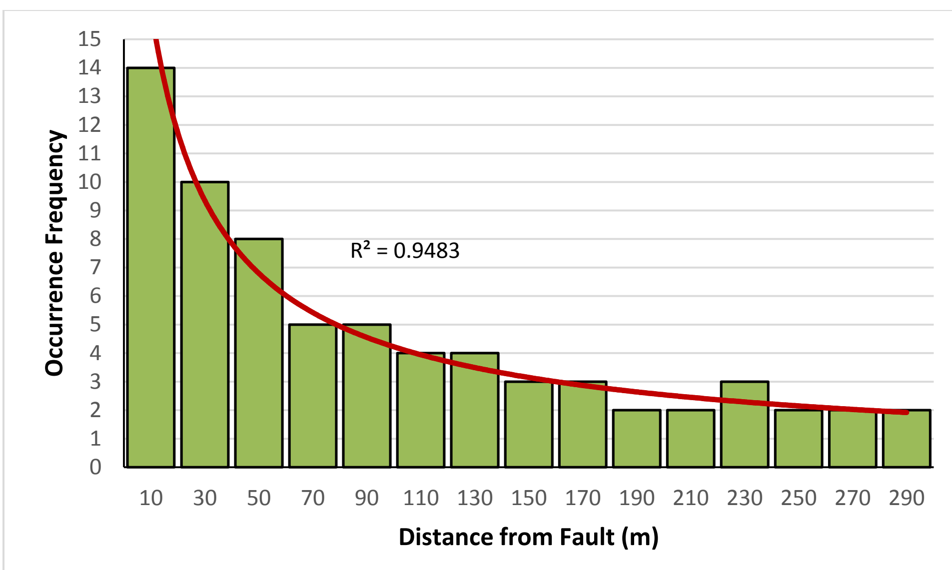
[16] Fisne & Olgun (2013)

Figure 11: Frequency distribution of locations of outbursts occurred in Kozlu and Karadon Collieries in Zonguldak Coal Basin[17]



Previous outburst studies (Fisne and Olgun, 2013) also found that outburst frequency increased with mining depth, inclination of the mined seam, seam thickness, and distance to faults. The most striking correlation is the nearness to faults as shown in **Figure 12**.

Figure 12: Outburst frequency relative to the distance from a known fault[18]



[17] Fisne & Olgun (2013)
[18] Ibid

Fisne & Olgun (2013) also presented Zonguldak outburst data as shown in **Table 5**.

Table 5: Largest outburst events in the Kozlu and Karadon mines[19]

Date	Coal Seam	Depth (m)	Amount of Ejected Coal (tons)	Amount of Emitted Gas (m^3)	Degassing Factor (m^3/tonne)
Nov., 1969	Sulu	402	120	7,000	58.3
Sep., 1974	Acılık	402	75	9,000	120.0
Dec., 1974	Acılık	401	80	7,000	87.5
Nov., 1975	Acılık	402	45	4,875	108.3
Jun., 1976	Büyük	396	60	4,600	76.7
Dec., 1980	Drift	418	80	7,200	90.0
Jul., 1987	Rabut	485	200	5,400	27.0
Feb., 2004	Messoğlu	548	620	16,000	25.8
Apr., 1974	Büyük	343	20	3,000	150.0
Apr., 1974	Acılık	343	70	8,000	114.3
Mar., 1975	Acılık	356	140	11,000	78.6
Feb., 2006	Messoğlu	560	600	16,000	26.7
May, 2010	Drift	540	80	25,000	312.5
May, 2011	Acılık	360	1,500	45,000	30.0
Apr., 2012	Acılık	460	595	17,850	30.0
Jan., 2013	Drift	630	2,040	65,000	31.9

The degassing factor, which is the estimated gas expelled divided by the volume of coal ejected, shows much more gas was liberated during the event than is either naturally contained within the coal or even what is emitted as specific emissions (**Table 3**). This implies gas pressure significantly over the Langmuir pressure which indicates storage of high pressure gas in the free gas state, possibly in porous fracture zones or bounding sandstones, or rapid drainage of adsorbed gas from remote locations.

Figure 13 shows the distribution of outbursts by seam based on 64 recorded outbursts.

[19] Fisne & Olgun (2013)

Figure 13: Outburst frequency by coal seam for both the Kozlu and Karadon mines[20]

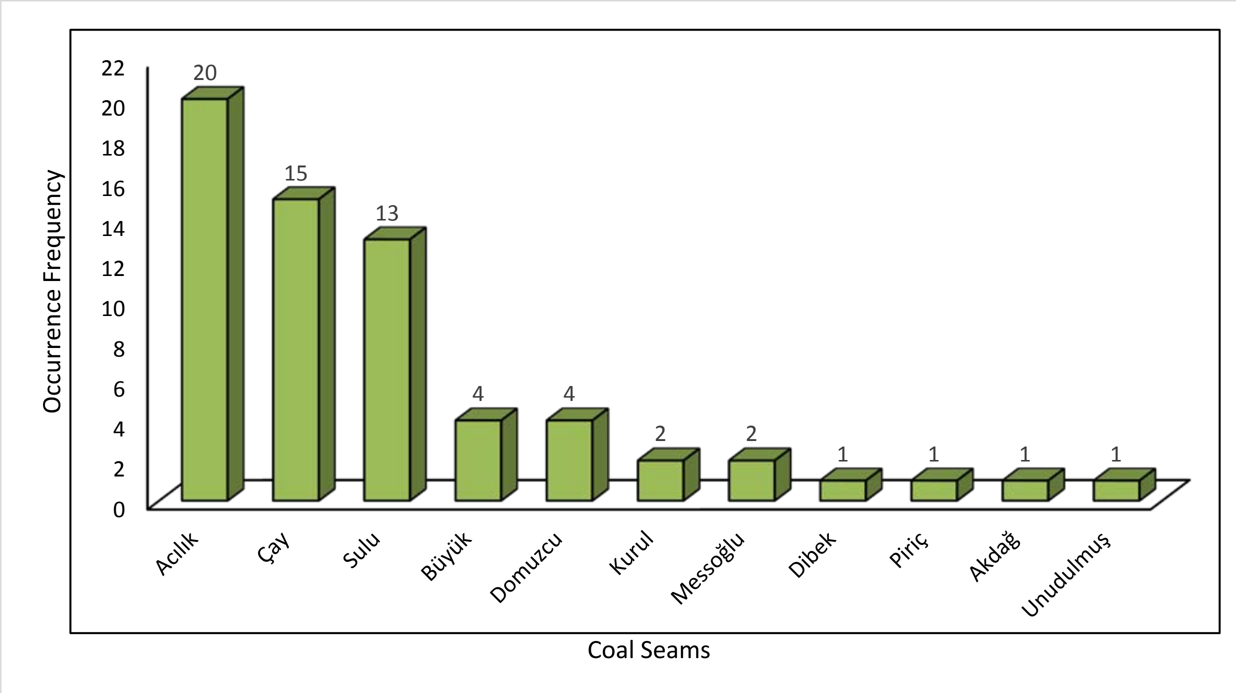


Table 6 and **Table 7** show average measured gas content values for the coal seams by depth in the Kozlu and Karadon mines, respectively. Gas contents over 10 m^3/tonne are considered to be very high. Considering the average values for the Kozlu mine, three of the seams are very gassy (Seams 25, 38 & 41) and two other seams are also relatively high (Seams 43 & 55).

Table 6: Kozlu high, low, and average measured gas content by seam[21]

Seam #	Coal Seam	# Samples	High (m^3/tonne)	Low (m^3/tonne)	Average (m^3/tonne)
25	Buyuk	1	NA	NA	11.72
30	Domuzcu	6	7.60	5.30	6.20
38	Rabut	2	12.80	12.82	12.81
41	Milopero	4	19.70	7.75	13.73
43	Hacimemis	5	13.50	5.20	8.00
44	Sulu	3	6.00	5.20	5.60
55	Cay	8	11.40	5.59	9.60

20 Fisne & Olgun (2013)
21 Fisne, A. (2013)

Table 7: Karadon high, low, and average measured gas content by seam[22]

Seam #	Coal Seam	# Samples	High (m^3/tonne)	Low (m^3/tonne)	Average (m^3/tonne)
	Akdag	2	5.33	5.30	5.32
25	Buyuk	2	12.10	8.20	10.15
30	Domuzcu	NA	NA	NA	NA
38	Rabut	NA	NA	NA	NA
41	Milopero	3	5.80	4.80	5.47
43	Hacimemis	1	NA	NA	6.64
44	Sulu	12	18.10	6.60	10.06
55	Cay	2	8.70	7.80	8.25

While the measured values show significant gas contents, they are not extreme and they do not necessarily correlate with the number of outburst events. Some other parameter must be causing the concentration of outbursts in Acilik, Cay and Sulu; possibly something simple, as these are the most heavily mined seams.

Other features influencing outbursts (e.g., geologic structures) will still play an important role but in any case, pre-mining gas drainage of gassy seams appears crucial.

6.0 Outburst Control Leading to CMM Capture and Utilization

Current practices at the Kozlu coal mine to control outbursts have proven inadequate. Currently there is no gas drainage system (i.e., vented in the mine workings); the design of the outburst control system is insufficient because the drill cannot reach the end of the heading development; and the drilling equipment cannot drill far enough ahead to enable outbursts to be located, discharged, and drained (current limit is 25 meters). (The limited reach of the drilling equipment means that outburst control techniques and corresponding management processes will continue to be ineffective.)

When assessing CMM drainage practices worldwide, poor outburst management practices and inadequate safety standards or equipment represent the biggest barrier to safely preventing an explosive atmosphere from forming. At the Kozlu mine, the central issue is not management practices, but a lack of financial investment in safety equipment (e.g., inadequate drilling equipment).

6.1 Drilling Equipment

The current drills are not powerful enough to drill the complete face distance for headings (60 to 100 meters). This means the heading is not drained prior to development of the angled roadway, and outbursts are common.

[22] Fisne, A. (2013)

6.2 Outburst System Design[23]

Discussions with TTK revealed that when an outburst is discovered at a drill site, drilling is stopped and a new, larger bore drill is used to re-drill the hole and increase its diameter. However, the borehole sealing does not appear to be adequate for sealing against an outburst. Moreover, this approach would likely cause the drillers to evacuate as soon as signs of a significant outburst were detected. Because the drill cannot reach the end of the heading development, the design of the outburst system is ineffective.

6.3 Gas Drainage System

When an outburst is detected, there is no means of removing the outburst gas released from the coal. This means that any gas or coal dust outburst is merely vented within the mine, which is a fundamental problem.

6.4 Management Processes

Discussions with TTK revealed that drilling personnel do not adhere to the drilling and drainage system instructions. However, the management processes associated with outburst control might be ineffective because the drilling equipment is not able to prevent outbursts.

6.5 Methodology and Estimated Cost for Improvement of Outburst Control

To prevent frequent outbursts and resulting injuries or fatalities, the following approach for improving safety within the mine is recommended:

1. Make improvements to the currently inadequate mine safety equipment.
2. Generate a budget to develop improved outburst control equipment and procedures.
3. Procure new lightweight, powerful in-mine drilling rigs with high-quality rods and bits that have the capacity to drill 60 to 100 meters.
4. Design and install a new methane drainage pipework system that is capable of extracting gas/dust away from the drill hole and then outside of the mine.
5. Install a new methane extraction plant (a suitable vacuum pumping station design is available).
6. Design a new outburst control system (incorporating the new drilling system and training for operators, methane drainage pipework, and methane extraction plant).
7. Develop new outburst management processes that are appropriate to the new equipment and drainage design.

Budget costs for recommendation #3 above are expected to be approximately $300,000 U.S. dollars (USD). After demonstrating the drilling equipment performs as recommended, it would then be appropriate (in a staged sequence) to install underground pipes. The cost of the underground pipes is entirely dependent on distance to mine shaft and pipe diameter/material, but the estimated cost would be in the range of $100,000 to $500,000 USD. Once the pipework is installed and the gas is discharged on the surface, a methane extraction plant could be installed (estimated cost $350,000 USD). The total

[23] The project team was unable to visit a drilling site underground due to safety concerns. A subsequent review of the drainage system was used to evaluate the outburst system design.

budget shown in **Table 8**, including external drainage design consultants and all equipment, training, and on the job practical instruction, would be approximately $1 million USD phased in over the course of two years.

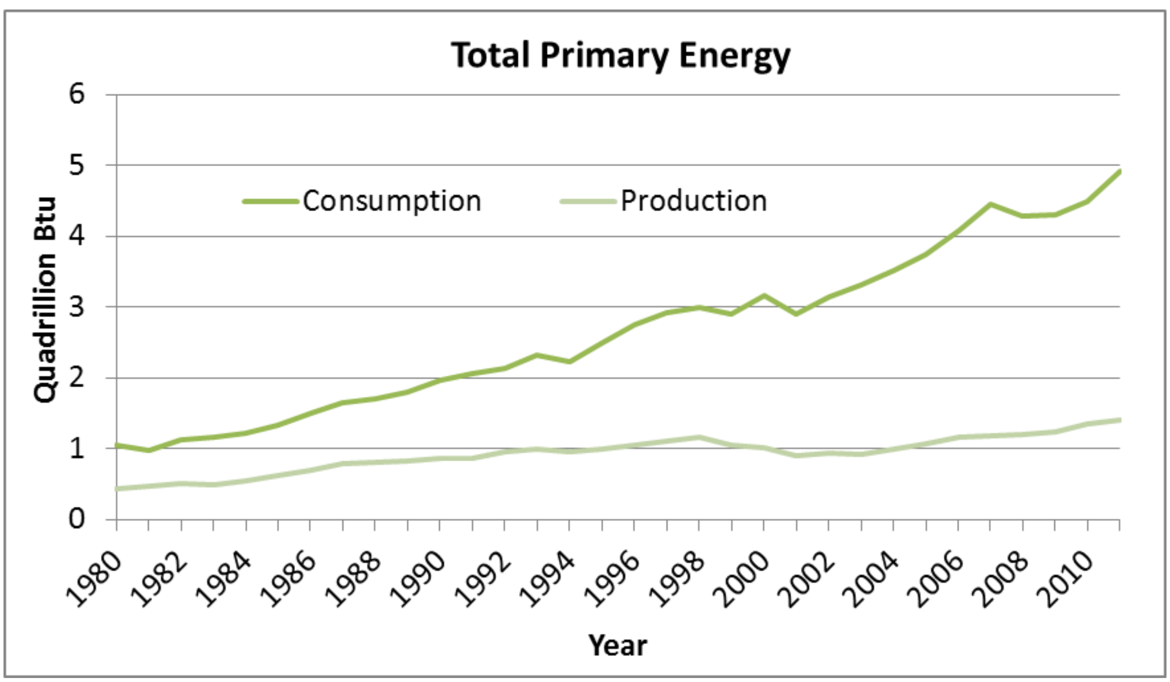
Table 8: Summary of estimated costs for improvement of outburst control

Equipment	Cost ($USD)
Drilling equipment	300,000
Underground piping	100,000 – 500,000
CH_4 extraction plant	350,000
TOTAL (installed)	**1,000,000**

7.0 Energy Market Information

Turkey has one of the fastest growing economies in the world with annual growth rates of more than 8% and corresponding demand for energy is expected to double over the next 10 years.[24] **Figure 14** shows that Turkey's annual energy consumption exceeds annual production, with a widening gap between production and consumption since 1980. In 2011, only one-third of Turkey's energy consumption could be satisfied by domestic energy production and approximately 71% of Turkey's energy use was provided by foreign fuel sources.

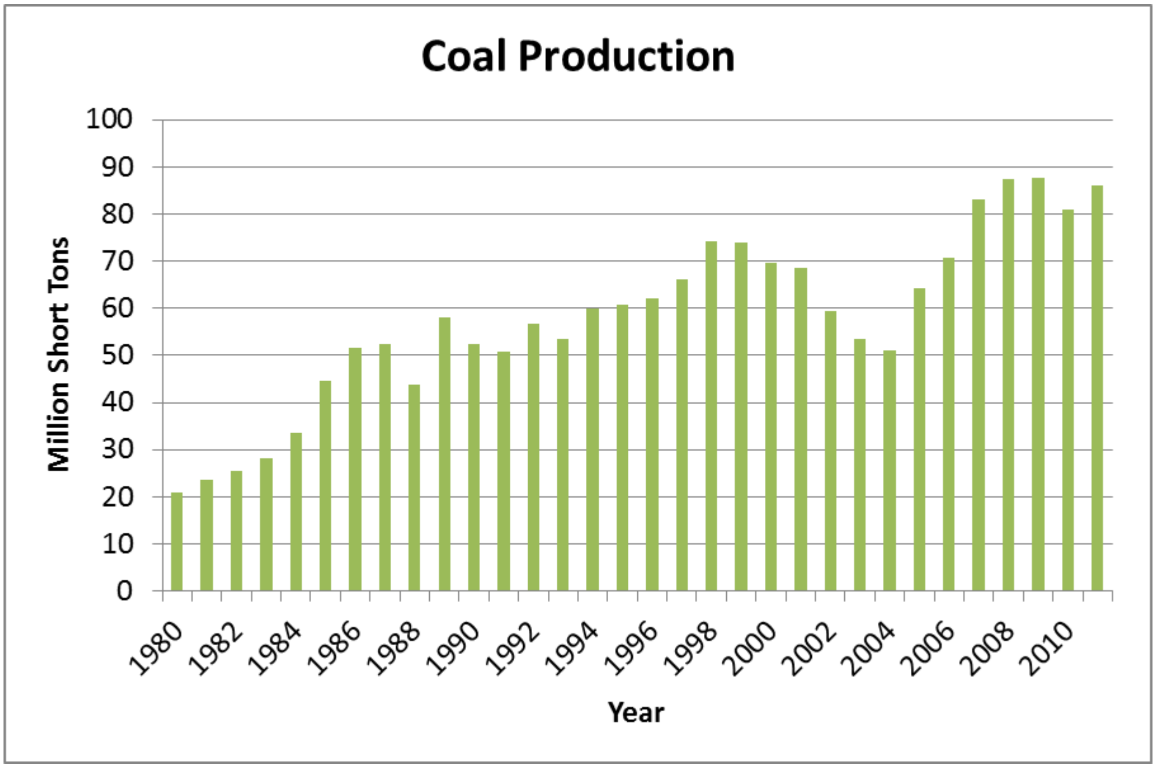
Figure 14: Turkey's total primary energy[25]



[24] EIA (2013)
[25] Ibid

Coal-fired power plants are a major energy source in Turkey. In 2011, approximately 30% of electricity came from the consumption of coal and lignite. Since 1980, coal production has generally increased, with a decline from 1999 to 2004 and a slight decline in 2009, as shown in **Figure 15**. According to the U.S. Energy Information Administration (EIA), there has been renewed interest in the recovery of Turkey's domestic coal. As of 2008, Turkey's recoverable coal reserves totaled 2.6 billion short tons of coal, with only about 23% (583 million short tons) of that as hard coal.

Figure 15: Turkey coal production[26]

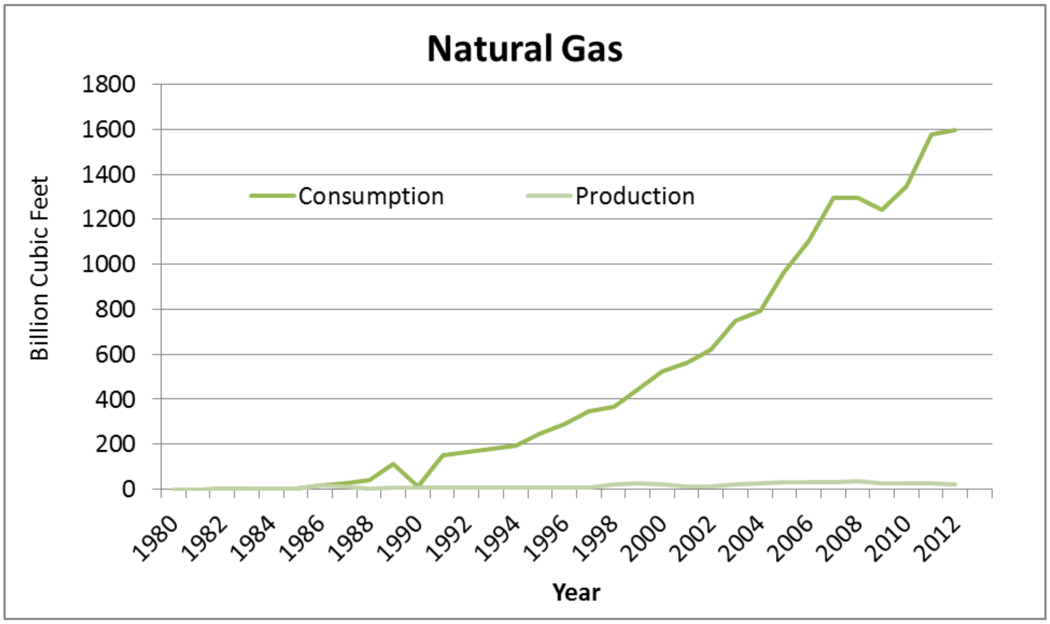


Natural gas is the largest fuel source consumed in Turkey, primary used in power generation and space heating.[27] In 2012, Turkey produced an estimated 22 billion cubic feet (Bcf) of natural gas and consumed approximately 1,600 Bcf of natural gas, relying almost entirely on gas imports (**Figure 16**). Installation of pre-drainage systems into areas surrounding coal seams would offset some of Turkey's high demands for foreign natural gas. Depending on the quality of the gas, these pre-drainage systems have the potential to contribute fuel directly into Turkey's natural gas distribution system.

[26] EIA (2013)

[27] Peng, L.S. (1990)

Figure 16: Turkey's natural gas consumption vs. production[28]



The relative contribution of fuel sources for Turkey's power generation is shown in **Figure 17**, which shows a significant hydropower sector.

Figure 17: Power generation by sector for Turkey in 2011[29]

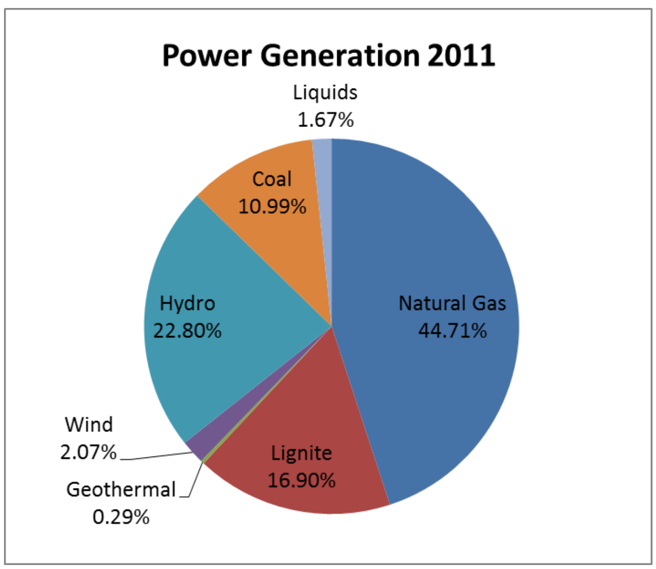


Table 9 shows the commodity prices for years 2011 and 2012 as reported by the European Commission. Note the gas prices converted from USD/kWh to USD/MMbtu are $11.72 and $8.79 for Household and Industry, respectively.

[28] EIA (2013)
[29] Ibid

Table 9: Turkey half-yearly electricity and gas prices[30]

	Electricity Prices				Gas Prices			
	Household (with VAT)		Industry (exclude VAT)		Household (with VAT)		Industry (exclude VAT)	
	2011	2012	2011	2012	2011	2012	2011	2012
EUR/kWh	0.122	0.131	0.079	0.086	0.029	0.029	0.022	0.022
USD/kWh	0.17	0.20	0.11	0.12	0.04	0.04	0.03	0.03

7.1 Carbon Market Participation

Turkey has been a major participant in the worldwide voluntary carbon market. In 2011, approximately 5 million voluntary carbon credits valued at $40 million entered the international market mostly from Turkish hydro projects. The Gold Standard and the Verified Carbon Standard are primarily the two programs under which Turkish projects are registered. According to the Turkish Carbon Market, Turkish projects made up approximately 39% of all the 2012 registered Gold Standard projects. The Gold Standard is preferred with an average 2011 price of about $10.40 over the VCS price of $3.70.[31] However, the Turkish Carbon Market estimates future demand for voluntary credits will not increase and opportunities for carbon projects are nominal without an increase in carbon market prices and demand.

8.0 End Use Assessment

Although the Kozlu mine is gassy, factors such as low gas permeability, the fractured nature of the coal geology, and the low, non-mechanized production rates mean CMM pre- or post- drainage techniques for methane capture prior are likely to be unsuccessful (distinctly separate from outburst control). At this time, it is recommended that outburst control be the priority. Where a new drilling, drainage, and extraction system might be implemented, the main target for these holes would be roadway gate developments; therefore, the drilled holes would be excavated by the developments and there would be no opportunity for long-term continuous gas extraction.

Currently, gas from coal production is controlled by ventilation only. Note that surface pre-drainage would be difficult because the incline of the seam is 30 to 60 degrees, and the fractured and non-homogeneous geology would prevent successful capture. Although it is possible that new gas drainage systems in mine could tap abandoned mine districts as gas sources, such districts might not be sealed in a tight manner; therefore, these are unlikely to be available.

Although the mine continues production using manual techniques, CMM drainage would generate gas only intermittently and at low gas volumes and methane concentrations. This means pipeline injection would not be technically or commercially viable. Although power generation using gas engines might be

30 European Commission (2013)
31 Peters-Stanley & Hamilton (2012)

intermittently technically viable at low gas volumes and concentrations, it would not prove to be commercially viable. However, gas flaring is considered to be a technical possibility, and this should be investigated as part of any methane extraction plant design or development.

At the time of the preparation of this study, the recommended technically and commercially viable option for CMM utilization is VAM to power, using RTOs coupled to waste heat recovery boilers and a steam turbine. The average methane concentration at the main mine ventilation shaft is >0.6% methane; therefore, there is sufficient heat energy in the gas to maintain self-sustaining operation of the RTOs and deliver excess heat via the hot gas bypasses (from each RTO) into a boiler and then to a superheater connected to an impulse steam turbine. Typical net cycle efficiency would be in the 18 to 28% range, depending on RTO design, boiler design, and steam turbine design.

The steam turbine manufacturing period is within the 9- to 12-month range; therefore, the project would have a 12- to 14-month implementation period.

It would also be possible to explore the use of RTOs interconnected to an Organic Rankine Cycle generator or a Rotary Screw generator. (These technologies are lower efficiency at around 15% net cycle efficiency.)

To develop this project, the high capital investment would demand a long-term power purchase agreement from the coal mine to buy the electricity—and possibly, revenue from carbon credits.

8.1 VAM Power Economics

The cost of power generation from VAM oxidation heat recovery was estimated for use in pro-forma economic analysis (before taxes and royalties). These are shown in **Table 10** together with the expected power generation. This is based on sizing for a Kozlu mine ventilation shaft with 0.6% methane concentration.

Table 10: Capital and operating and maintenance costs for low and high efficiency power production from VAM oxidation[32]

	Capital Cost, $	O&M Cost, $/Yr	Power, MWe	Efficiency
High Efficiency	13,360,000	668,000	1.35	28%
Low Efficiency	6,680,000	668,000	0.90	18%

To achieve an economically feasible project, a 15% rate of return for the high efficiency design was selected in order to offset the significantly higher cost of the initial investment. In order to achieve a 15% return, the following economic analysis shows that using current industrial power sales prices of 0.12 $/kWhr (**Table 9**) and current carbon prices on the voluntary market of 2.00 $/t$CO_2$e will not provide a positive rate of return. An economic model was run to determine what power price and what

[32] Butler, N. (2014)

carbon price might be needed to provide a hurdle rate of return of 15%. This—together with the 10% NPV and years to capital pay-out—are shown in **Table 11** and **Table 12***.

Table 11: Economic results for high efficiency VAM power unit (Power and carbon prices needed to achieve 15% return)

	Current Prices	High Power Price	High Carbon Price
Power Price, $/kWhr	0.12	0.24	0.12
Carbon Price, $/tCO2e	2.00	2.00	30.00
Rate of Return, %	Not applicable	15%	15%
10% NPV, USD	($6,260,976.56)	$3,551,696	$3,409,808
Pay-out, years	Not applicable	6	6

Table 12: Economic results for low efficiency VAM power unit (Power and carbon prices needed to achieve 15% return)

	Current Prices	High Power Price	High Carbon Price
Power Price, $/kWhr	0.12	0.22	0.12
Carbon Price, $/tCO2e	2.00	2.00	21.00
Rate of Return, %	Not applicable	15%	15%
10% NPV, USD	($3,431,509.25)	$1,856,431	$1,753,473
Pay-out, years	Not applicable	6	6

* Both a higher power price and a higher carbon price are required to achieve a 15% rate of return for the high efficiency design in order to offset the significantly higher cost of the initial investment.

9.0 Observations and Recommendations

The following are some initial observations and recommendations for controlling outbursts, improving mine safety, and exploring a future CMM utilization project at the Kozlu mine:

- Generate a budget for improved equipment and procedures for outburst control.
- Procure new lightweight powerful in-mine drilling rigs with high quality rods and bits that have the capacity to drill 60 to 100 meters and train personnel on usage of the equipment.
- Design and install a new methane drainage pipework system in the mine capable of extracting gas/dust away from the drill hole and then away to the outside of the mine.
- Install a new methane extraction plant (a suitable vacuum pumping station design is available).
- Develop a new outburst control design and implementation protocol (incorporating the new drilling system and training for operators, methane drainage pipework, and methane extraction plant).
- Develop new outburst management processes that correspond to the new equipment and drainage design and procedures.

- Once these outburst control recommendations are established, drainage volumes and gas quality should be monitored to determine the feasibility of establishing a technically and economically feasible end use technology for the mine methane.

10.0 Conclusions

The objective of this pre-feasibility study, commissioned by USEPA, is to develop recommendations to reduce methane gas outbursts in the Kozlu coal mine and evaluate the potential to capture methane for utilization. Based on a meeting with TTK and a preliminary analysis of the information gathered during a site visit, the Kozlu coal mine was selected for this pre-feasibility study due to opportunities for improving safety (i.e., reducing outbursts) and CMM recovery and utilization.

Turkey's hard coal resource is restricted to a relatively small area along its northwest coast of the Black Sea. The coal measures are composed of numerous seams with high gas content. Mining conditions are extremely difficult because of intense faulting and folding of the strata with inclinations of up to 90 degrees. Difficult mining conditions, together with high gas contents and low permeability, have led to numerous coal outbursts, many of which have been catastrophic. Because of the complex nature of the geology, mechanized mining methods cannot be used so the mining is very labor intensive, exposing many miners to the hazards posed by the outburst conditions.

Coal outbursts occur in all major coal basins of the world and are generally controlled with pre-mine drainage. At the Kozlu mine, current practices to control outbursts have proven inadequate. Currently there is no gas drainage system (i.e., vented in the mine workings); the design of the outburst control system is insufficient because the drill cannot reach the end of the heading development; and the drilling equipment cannot drill far enough ahead to enable outbursts to be located, discharged, and drained. (The limited reach of the drilling equipment means that outburst control techniques and corresponding management processes will continue to be ineffective.)

To prevent frequent outbursts and resulting injuries or fatalities, the Kozlu mine should make improvements to the currently inadequate mine safety equipment; generate a budget to develop improved outburst control equipment and procedures; procure new in-mine drilling rigs that have the capacity to drill 60 to 100 meters; design and install a new methane drainage pipework system that is capable of extracting gas/dust away from the drill hole and then outside of the mine; install a new methane extraction plant; and design a new outburst control system and management processes (e.g., worker training).

With an investment of approximately $1 million USD, adequate equipment and training can be obtained that will dramatically reduce the probability of catastrophic coal outbursts at Kozlu. While outburst control should be a first priority moving forward at the Kozlu mine, establishing an in-mine drainage system to take the drained gas to a surface pumping station where it can be flared would also reduce the mine's GHG emissions. The ventilation air at the Kozlu mine was found to be greater than 0.6% methane, which could be sufficient for VAM oxidation together with steam power generation. However, using current power sales and carbon sales price does not generate sufficient economic return. A significant premium in either power sales price and/or carbon credit price would be required to provide a hurdle rate of return of 15%. Finally, after the outburst control recommendations are fully implemented and under control, drainage volumes and gas quality should be monitored to determine the feasibility of establishing a technically and economically feasible recovery and use project for the mine methane.

11.0 References

Butler, N. (2014): Personal communication between Neil Butler, Harworth East Limited, and Ronald Collings, Ruby Canyon Engineering.

EIA (2013): U.S. Energy Information Administration: Turkey: Country Analysis Brief Overview. www.eia.gov/countries/country-data.cfm?fips=TU.

European Commission (2013): "Energy Price Statistics." epp.eurostat.ec.europa.eu/statistics_explained/index.php/Energy_price_statistics.

Fisne, A. (2013): Personal communication between Dr. Abdullah Fisne, Istanbul Technical University, and Ronald Collings, Ruby Canyon Engineering.

Fisne, A. and E. Olgun (2013): "Coal and Gas Outburst Hazard in Zonguldak Coal Basin of Turkey, and Association with Geologic Parameters" (pre-publication), Istanbul Technical University, Mining Engineering Department.

Hosgormez, H. (2007): Origin and secondary alteration of coalbed and adjacent rock gases in the Zonguldak Basin, western Black Sea Turkey. Geochem J 41:201-211.

Okten, G., A. Fisne, T. Hucaverol, C. Onur and E. Gunay (2011): "Assessment of Coal and Gas Outburst Hazards in Zonguldak Coal Basin, Turkey," 22nd World Mining Congress & Expo, September 2011, Istanbul, Turkey. NOTE: Presentation is not available online.

Ozturk, M. (2013a): Personal communication between Mesut Ozturk, Turkish Hardcoal Enterprises (TTK), and Ronald Collings, Ruby Canyon Engineering.

Ozturk, M. (2013b): Introductory Notes on Turkish Hardcoal Enterprise (TTK), Mesut Ozturk, TTK.

Peng, L.S. (1990): *Introduction to gas-geology*. Beijing: China Coal Industry Publishing House. NOTE: Publication is not available online.

Peters-Stanley, M. and K. Hamilton (2012): "Developing Dimension: State of the Voluntary Carbon Markets 2012." Ecosystem Marketplace and Bloomberg New Energy Finance. www.forest-trends.org/documents/files/doc_3164.pdf.

Shepherd, J., L.K. Rixon, and L. Griffiths (1981): “Outbursts and geological structures in coal mines: a review.” Int J Rock Mech Min Sci Geomech Abstr 1981; 18(4):267–83. NOTE: Journal access can be obtained at www.sciencedirect.com/science/article/pii/014890628191192X.

Toprak, S. (2009): Petrographic properties of major coal seams in Turkey and their formation. Int J Coal Geol 78:263–275. NOTE: Journal access can be obtained at www.sciencedirect.com/science/article/pii/S0166516209000433.

Virginia Polytechnic Institute and State University (Virginia Tech) Virginia Center for Coal & Energy Research (2012): “Optimizing Degasification Systems to Reduce Methane Emissions from Turkish Coal Mines,” Blacksburg, VA.