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Potential Usage of Underground Mined Areas in Estonian Oil Shale Deposit

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted to any institution for any academic degree.

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Altkaevandatud alade kasutamine Eesti põlevkivimaardlas

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TTÜ KIRJASTUS

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PAPER II — **Karu, V.** (2012). Dependence of land stability on applied mining technology. 11th International Symposium "Topical Problems in the Field of Electrical and Power Engineering", Doctoral School of Energy and Geotechnology, Pärnu, Estonia, 16-21.01.2012, p. 252-255.

PAPER III — Erg, K.; **Karu, V.**; Lind, H.; Torn, H. (2007). Mine pool water and energy production. 4th International Symposium "Topical problems of education in the field of electrical and power engineering" Doctoral School of Energy and Geotechnology, Kuressaare, 15-20.01.2007. (Ed.) Lahtmets, R. Tallinn University of Technology Faculty of Power Engineering, p. 108-111.

PAPER IV — Valgma, I.; Tammeoja, T.; Anepaio, A.; **Karu, V.**; Västrik, A. (2008). Underground mining challenges for Estonian oil shale deposit. Schacht, Strecke und Tunnel, TU Bergakademie. Buhrow, Chr.; Zuchowski, J.; Haack, A. (Ed.). Freiberg, p. 161-172.

PAPER V — Valgma, I.; Robam, K.; **Karu, V.**; Kolats, M.; Väizene, V.; Otsmaa, M. (2010). Potential of underground mine water in Estonian oil shale mining region. 9th International Symposium Pärnu 2010 “Topical Problems in the Field of Electrical and Power Engineering” and “Doctoral School of Energy and Geotechnology II”, Lahtmets, R. (Ed.), Pärnu, Estonia, June 14-19, 2010, Estonian Society of Moritz Hermann Jacobi, p. 63-68.

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PAPER VII Valgma, I.; **Karu, V.**; Anapaio, A.; Väizene, V. (2007). Increasing oil shale quality for meeting EU environmental requirements. Mining and the Environment 2007, Baia Mare, TU Freiberg, p. 195-205.

PAPER VIII **Karu, V.**, Västrik, A., Anepaio, A., Väizene, V., Adamson, A., Valgma, I. (2008). Future of oil shale mining technology in Estonia. Oil Shale. Volume 25, No. 2 Special, p. 125-132.

PAPER IX Valgma, I.; Reinsalu, E.; Sabanov, S.; **Karu, V.** (2010). Quality control of oil shale production in Estonian mines. Volume 27, No 3, p. 239-249.

1. Introduction

Oil shale mining has a crucial meaning for Estonian economy. More than 90% of electricity in Estonia is produced from oil shale which has been mined for over 90 years with the total production exceeding one billion tonnes. The oil shale deposit is located in the north-eastern part of Estonia (Figure 1). Objects of this study are shown in Figure 2. The oil shale bed descends 3m per kilometer towards the south (Figure 3) and the oil shale seam consists of interlayered limestone (Table 1) which is a waste rock stored in waste rock heaps. Oil shale is mined using two methods: underground (room and pillar mining method) and from the surface (open cast mining method) [1]. The former method of oil shale mining created underground free space and, as mining had been carried out below the groundwater level, the workings filled with water after their closure. Estonian oil shale deposit comprises ten closed mines that are fully or partly filled with water. Eight mines in the central part of the deposit - Ahtme, Kohtla, Kukruse, Käva, Sompa, Tammiku, Mine No. 2 and Mine No. 4 - form one water body. Ubja mine and Kiviõli mines are located in the western part of the deposit, further away from other mines [2].

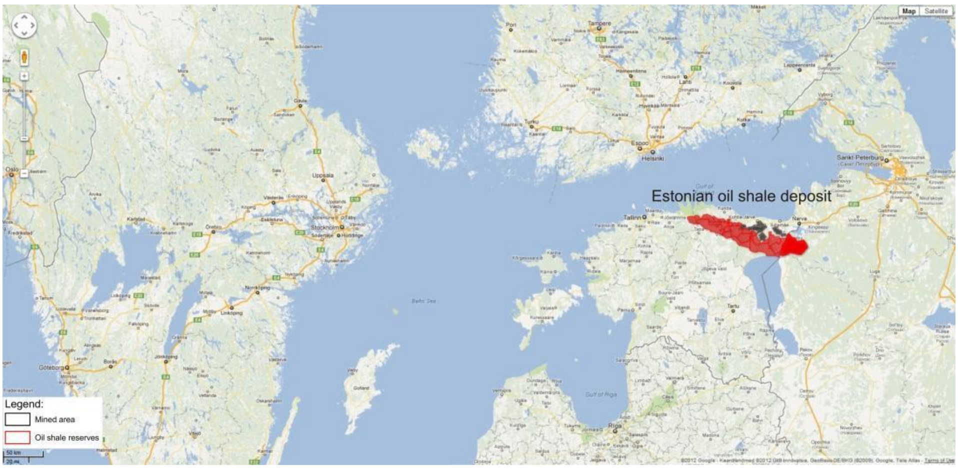

Figure 1 Location of Estonian oil shale deposit [3; 4; 5]

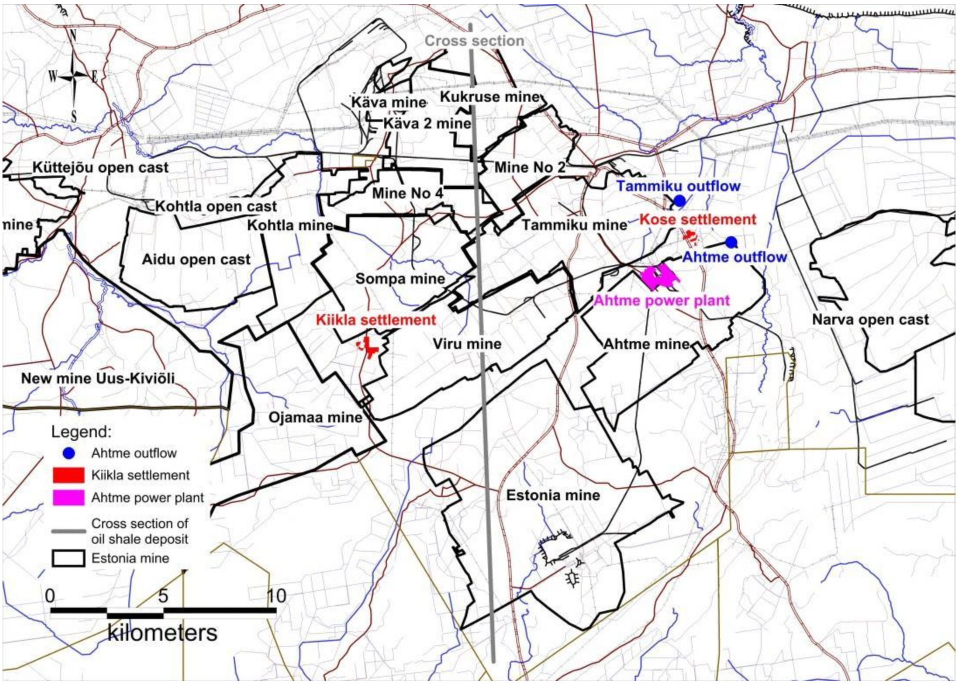

Figure 2 Objects of the study

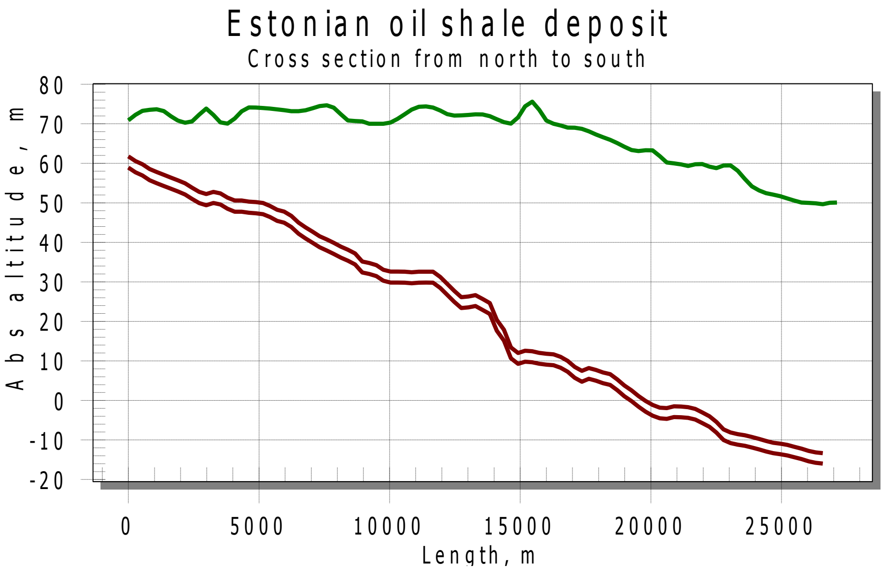

Figure 3 Cross section of Estonian oil shale deposit

Table 1 Oil shale stratum [1; 6]

Lithology	Layer	Layer thickness, m	Height from layer A, m
	F2	0.30	3.03
	F1	0.34	2.73
	E	0.59	2.39
	D/E	0.10	1.80
	D	0.07	1.70
	C/D	0.29	1.63
	C	0.45	1.34
	B/C	0.08	0.89
	B	0.37	0.81
	A/B	0.21	0.44
	A	0.23	0.23

The subject of the current thesis became topical several years ago and encompassed many research and commercial projects connected with it. The projects dealt mainly with two issues: stability of undermined areas and mine water balance. As to stability, recommendations were given on how to conduct different building projects in undermined areas [7; 8; 9; 10; 11; 12; 13; 14; 15; 16; 18; 19; 20]. Mine water balance projects studied the possibilities of mine water usage as a heat source for heat pumps and the amount and distribution of mine water in the seam [7; 8; 9; 13; 14; 15; 16; 17]. Development and exploitation of water resources is critical for a viable and sustainable modern human society. Unfortunately, however, there is a considerable water storage depletion and environmental degradation in especially (semi)-arid river basins due to the forces of population growth, urbanization, industrialization and intensive agricultural irrigation [21].

Filling of underground oil shale mines creates underground water pools called technogenic water bodies with all-year stable temperature. These water bodies have a potential use as a heat source for heat pumps and reduction of winter-time heating costs. Relations between applied mining technologies, underground space, hydrogeological parameters of closed or abandoned mines and subsided areas have to be investigated before mine water can be used as a heat source for heat pumps. The aim of this research is to calculate the amount of mine water in closed or abandoned oil shale mines in the central part of Estonian oil shale deposit and offer solutions for usage of undermined areas.

The objectives of this study are:

1) Determination of water amount in underground mines;
2) Technological solution for using a heat pump complex
3) Planning of land use in undermined areas;
4) Defining underground space;
5) Properties and classification of applied mining technologies;
6) Water requirements for a heat pump;
7) Creation and evaluation of hydrogeological parameters for closed or abandoned mines.

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2. Parameters

The list of applied parameters and values presented in Table 2 illustrates the results of the accomplished work. The parameters are listed in the order they were used in calculations, models, and modelling. Each step of computations required analysis and decisions on what kind of values to use before going ahead in modelling.

Table 2 An overview of used parameters

Parameter	**Symbol**		**Example**	**Unit**
Evaporation rate	E	=	300	mm/y
Rain factor	a	=	0.11	m^3/y.mm
Specific yield	Sy	=	0.14	
Specific yield	Sy	=	14	%
Specific storage	Ss	=	4.5	1/m
Hydraulic conductivity	K	=	10	m/d
Horizontal hydraulic conductivity	Kx,y	=	30	m/d
Vertical hydraulic conductivity	Kz	=	3	m/d
Mining area	S	=	141.1	m^2
Bottom of screen	Vp	=	33	m
Top of screen	Vl	=	35	m
Screen elevation	Vh	=	42	m
Amount of pumped out water	Qp	=	3822	m^3/h
Thickness	hk	=	20	m
Effective porosity	n	=	15	%
Effective porosity	n	=	0.15	
Porosity	p	=	30	%
Porosity	p	=	0.3	
Precipitation	P	=	853.3	mm/y
Technogenic porosity	n_t	=	1.83	milj m^3
Width of the water barrier	l	=	50	m
Length of the water barrier	L	=	6.7	km
Amount of water permeating the barrier per one hour	q	=	28	m^3/h
Observation time	t	=	7300	day
Stop time	w	=	7300	day
Permeability	K	=	393	m^2/d
Water volume	Q	=	24.8	milj m^3
Observation head	hv	=	35	m
Initial head	hi	=	42	m
Difference between water levels	dh	=	20	m
x-coordinate (Estonian coordinate system)	X	=	697386.852	m
y-coordinate (Estonian coordinate system)	Y	=	6580306.41	m

3. Methods

An important step in the procedure of building an environmental model is the transformation of a conceptual model into numerical simulation. To simplify model construction, a framework is required that relieves the model developer from software engineering concerns. In addition, as the demand for a holistic understanding of environmental systems increases, an access to external model components is necessary in order to construct integrated models [22; 24; 26; 27; 28].

There are several mining software programs that are either freeware (different viewers), independent (GEMCOM Surpac and Minex, MapInfo, AutoCAD, ESRI etc.) or additional programs (Discover, Map X etc.) as well as online software programs (EduMine etc.) [29; 30]. There are problems in the compatibility of the projects as different institutions use different software systems. When developing co-operation, there are difficulties in connecting and transferring the data, which in its turn poses an economical problem – designers have to have as many different software packages as possible for the co-operation to work [PAPER I; PAPER II; 75; 76].

The underground space and its properties should be defined in order to determine the stability of undermined areas and calculate the potential amount of water. The situation has to be mapped in 3D as the underground space is created by mine workings, roof structure and related water channels or tubes. Hydrogeological parameters have to be established and evaluated to determine the underground space properties and classification of used mining technologies.

The classification helps to define the space that is available for water in abandoned mines. The method and computer program have been developed in order to assess the underground mined area of the oil shale deposit and to describe the extent of influence of mining operations. It provides an opportunity to evaluate the condition of the ground and, taking possible risks into consideration, plan the use of the ground and construction actions. The computer program enables us to calculate the types of land emerging as the result of certain mining methods: quasistable land and subsided land. The calculation method exploits the geological dataset, plan of mining operations and subsidence caused by mine work. The computer program uses an algorithm to calculate the mining impact areas that are affected by mining (steady, stable, quasistable, and subsided land) [PAPER II; 31; 32; 76].

The main tools for analysing the amount of water in abandoned oil shale mines is computational modelling with spreadsheet models and designing the water flow with program MODFLOW. For computational modelling we need to know the mining technology of the oil shale bed, amount of space in the old mine drifts and movement of water between the mines. The model enables us to assess the water levels in different mines and their border areas and make assumptions and predictions about the directions of water movement [PAPER III; PAPER V; PAPER VI; 77; 79; 80].

The oil shale block model, created with the help of topographic and geological data (stratigraphy, hydrogeology, LIDAR [1]data), helps to describe the mining conditions i.e. geological, technological and environmental conditions that directly affect oil shale mining. The most common of them are oil shale layer thickness, depth, angle and rock stability. The model shows top layers: the surface, layers of limestone, oil shale seam and ground water levels and enables us to choose the best available technology for oil shale mining using the knowledge of the mining conditions.

MODFLOW is a groundwater modelling program which can be compiled and remedied depending on its practical applications. Because of its structure and fixed data format, MODFLOW can be integrated with Geographic Information Systems (GIS) technology for water resource management [33]. MODFLOW calculation models are widely used in different regions of the word, e.g. India, China and Canada [33; 34; 35]. Modelled pumping tests have also produced positive results and recommendations for change of action [36].

[1] LIDAR – Airborne Laser Scanning

4. The study area and data collection

4.1. Oil shale mining area

Despite the shallow depth of the oil shale bedding the underground mining method has been used in several locations instead of the surface method [23]. Underground oil shale mining has been applied for ninety years in Estonian deposit in the middle-north part of Baltic oil shale deposit (Figure 4; Figure 6) [24; 25]. The shallow depth of the central-northern deposits, their greater thickness and better quality were the reasons why mining started from Kukruse in 1916, moving towards the edges of the deposit where mining conditions worsen. The technology mostly used in the northern part of the deposit was hand-mining technology and longwall mining (Figure 4) with the application of the room and pillar method in newer mines from the 1950-1960's (Figure 6). Nine closed oil shale underground mines and two operating mines are located in the study area (Table 3).

Table 3 Closed oil shale mines in the study area

Options	Kukruse	Mine No 2	Käva	Käva 2	Mine No 4	Tammiku	Sompa	Kohtla	Ahtme
Mine opening	1921	1949	1924	1924	1953	1951	1948	1937	1948
Mine closing	1967	1973	1972	1972	1975	1999	1999	2001	2001
Working time, year	46	24	48	48	22	48	51	64	53
Field area, km^2	13.20	12.30	3.47	14.05	12.70	40.00	33.60	18.30	43.30
Mined field area, km^2	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36
Unmined area, km^2	-1.93	3.73	1.63	2.33	2.27	20.74	15.46	6.16	16.94
Thickness of overburden, m	11	13	21	10	12	23	23	15	37
Thickness of oil shale seam, m	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Geological space in oil shale seam, million m^3	**42.82**	**24.08**	**5.22**	**33.05**	**29.20**	**53.92**	**50.24**	**33.52**	**73.53**

Oil shale mining methods have changed several times over the years due to geological conditions, technology, mining method developments, etc. The following is a short overview of formerly and currently applied oil shale mining methods in Estonian mines.

Hand mined area (rooms and longwall). In areas where hand mining method (rooms and longwall) was in use, the extracted layer thickness was 2.2-2.3 m from the oil shale bottom layer (layer A, see Figure 9). In case of the hand mined method the oil shale was loaded to the hutch while waste rock (limestone) was thrown to the mined area and a limestone wall was created (Figure 5). This caused smooth subsidence of overburden layers to the limestone walls. Land subsidence kept occurring during a few months after mining. Smaller subsidence may occur up to two years after mining, and subsequently these areas can be counted as stable. However, some subsidence may occur three to four years after mine closure when the mine is filling with water.

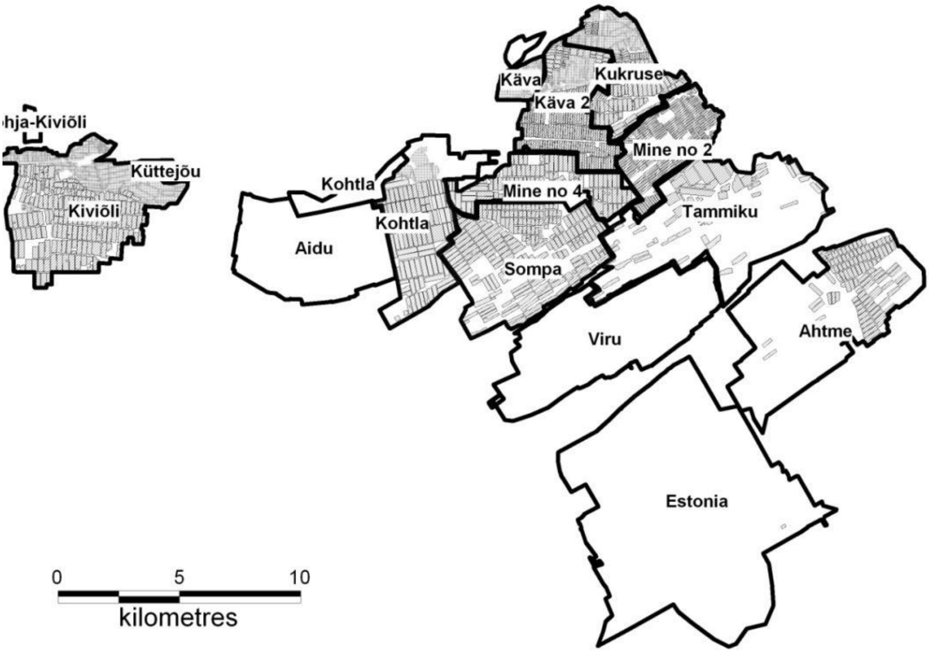

Figure 4 Hand-mined areas and mechanised longwall areas, marked with hatching

Figure 5 A hand-mined area after oil shale extraction. Limestone was put to mined area into the limestone wall (An example from Kohtla Mining Museum)

Mining with longwall shearers. Estonia has thirty years of experience in cutting with longwall shearers, the extracted layer thickness being 1.5-2.4 m with panels 180 m wide and up to 600 m long. The longwall shearers, however, did not cut the hardest limestone layer inside the seam and road headers were tested for the purpose in the 1970's.

Room and pillar mining method. The main current underground mining method is room and pillar mining (Figure 6). The oil shale mines fields are divided into panels by panel drifts. The panels, 600 to 800 m wide and several kilometres long, are then divided into 350 m wide mining blocks. The main operations carried out in rooms include bottom cutting, drilling of blast holes, blasting, loading of blasted rock on the chain conveyer and supporting the roof by bolts. The height of the rooms corresponded to the thickness of the commercial oil shale bed, which was mostly 2.8 m. Today, the height in Estonian oil shale mines is up to 3.8 m with a new room and pillar method, while the width of the workings varies from 6 to 10 m. The largest difference compared to other oil shale mining technologies is the remaining room and the overburden supported by pillars formed during mining operations. Therefore there is a large amount of free space in mined areas where mine water can accumulate (Figure 7).

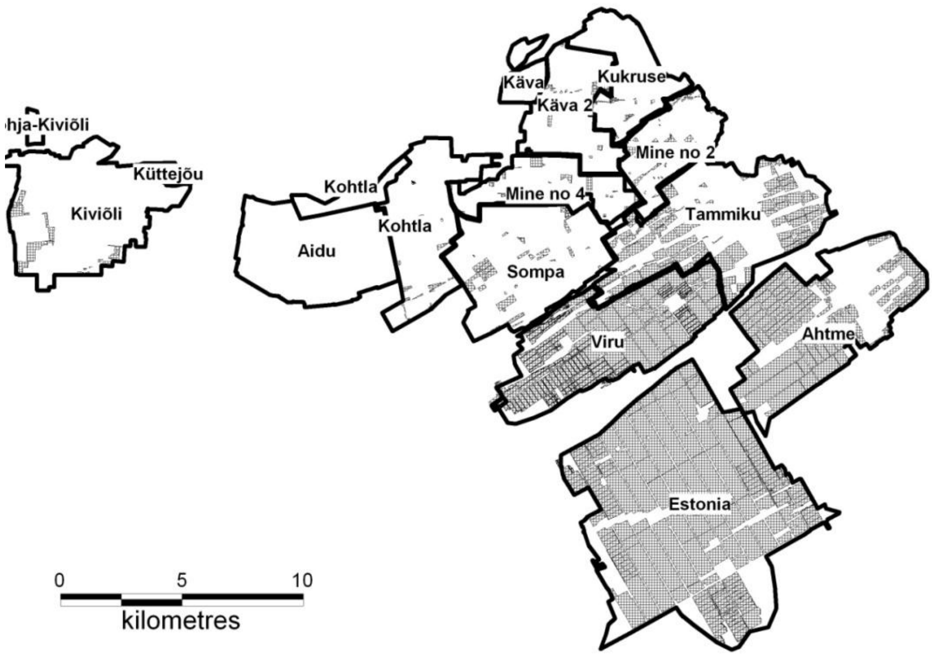

Figure 6 Room and pillar mining areas, marked with hatching

Figure 7 Room and pillar mining leaves underground free space (the Estonia mine)

The undermined area. Underground mined areas are complex and there are problems with predictability of their stability faced not only in Estonia but also elsewhere in the world. Stability of underground mined areas is conditioned by many factors (e.g. extraction time, technology, the thickness of the extracted seam), some of which are very difficult to identify or even unknown. Calculation and assessment methods are based on simplified models which are rather adequate for yielding practical results. It is quite complicated to determine the conditions of land stability in Estonian underground mined areas for later road construction or other service areas. Land stability determination is related to various mining method parameters (e.g. thickness of the layer, type of support, etc.).

4.1.1. Classification of underground mined areas

There are many closed mining sites in European countries [37; 38; 39; 44]. Closed underground mines may influence ground stability related to mining activities and underground space creation [40; 41; 42].

During the ninety years, different mining technologies have been used in Estonian oil shale deposit. The price of extracted oil shale, evaluation method and results of land stability assessment depend on the applied mining technology

(Figure 8). The calculation method described above is employed to calculate areas with different levels of stability (steady, stable, quasistable, subsided).

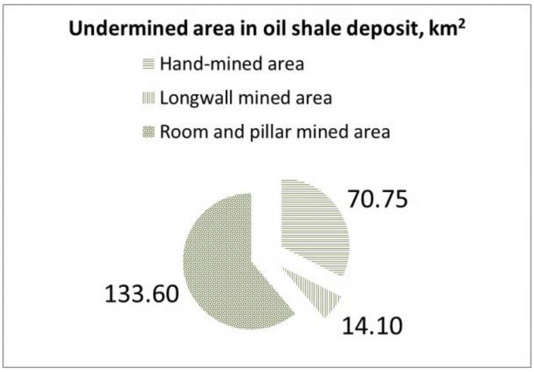

Figure 8 Proportions of different mining methods in the undermined area

The mining method and geological conditions determine the size of pillars and underground rooms, use of longwall and other accompanying details. Therefore, the volume of empty space in various undermined areas is different. Depending on groundwater level the free space in extracted oil shale seam fills with mine water to an alternating extent. Maximum free space in different undermined areas is shown in figure (Figure 9).

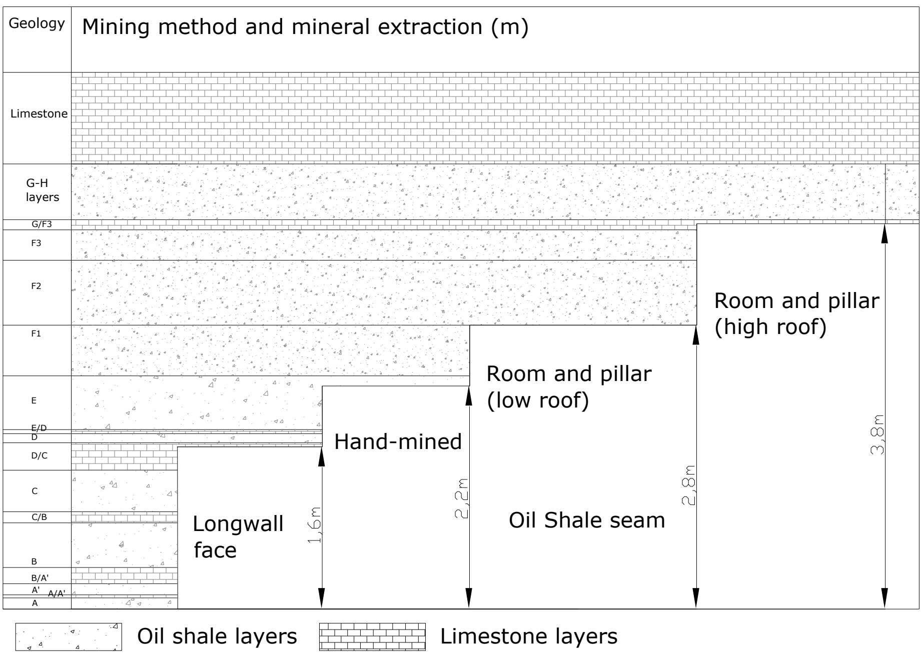

Figure 9 Maximum free space after mining workings in an oil shale seam

Analysis of various mining plans (including old ones), mining maps, geological conditions, production schedules, and other aspects gives an idea of which technology is appropriate to apply in a certain mine (Figure 10). Used mining technology determines the amount of free space remaining after the end of mining operations [PAPER II; 76].

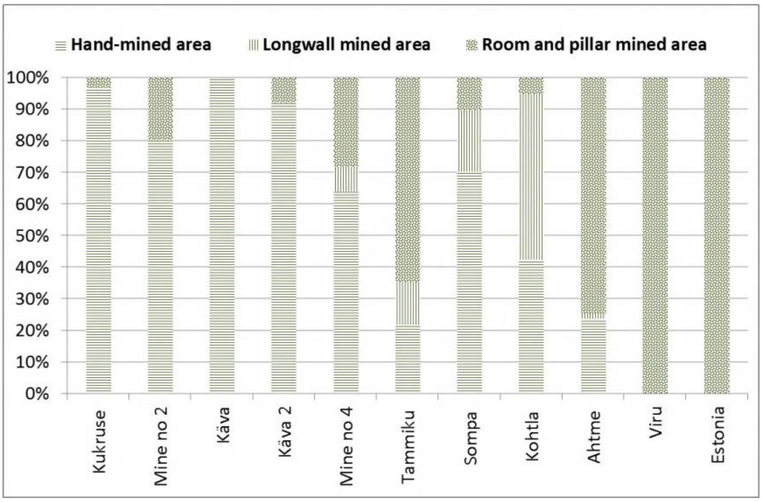

Figure 10 Proportions of used mining technologies in mined fields

Classifications of underground mined areas have been assessed in previous studies [1; 12; 31]. Limitations for buildings and land use in undermined areas have also been considered (Table 4) [31].

Steady land is unmined land located in the proximity of protective or remnant pillars of the mining claims. The areal extent of the steady land is always smaller than the areal extent of the pillar.

Subsided land is located above the hand-mined areas where advancing and retreating mining and longwall mining with double-unit-face were used. The relief of subsided land depends on the quantity of filling material and the quality of filling and the roof structure. The applied mining technology and mining conditions determine the situation in the subsided land of an oil shale deposit.

Stable land is located in pillar-protected areas. Land stability depends on the strength of pillars, width of rooms and drifts. The drifts were designed so narrow as to prevent collapses in top layers. Stable land covers the rooms whose pillars were not mined before abandoning and the thickness of the hard roof remains in the range of 10-35 m. Secondary subsidence may occur in the areas with thinner limestone cover.

Quasistable land area forms in places where pillars hold mine workings during mining but may break afterwards. All the room and pillar mining area that is unstable is quasistable. Quasistable areas are also found by the sides of caved longwall mining areas, and above drifts, adits, and galleries on areas of mining at a shallow depth.

Table 4 Limitations for building and land usage depending on the type of underground-mined land [31]

Type of land	Buildings, roads, etc	Agricultural and forest land
Steady	No limitations	
Stable	Only light buildings	No limitation
Subsided	Depends on the possibility of size and nature of land deformations in the future	Depends on possible changes of humidity regime caused by, especially unfavourable composition of Quaternary sediments
Quasistable	Generally building is forbidden, permission only for projects which have passed geotechnical expertise	The risk of destroying cultivations caused by, especially unfavourable composition of Quaternary sediments

It is not possible to give general recommendations and permissions for building, road construction or other land usage as every specific case has to be solved separately, depending on the mining conditions and method [PAPER II; 32; 43; 49]. If reclaiming is planned skilfully, the soil, landforms, forest, water bodies and agricultural land can be more valuable than before mining [45; 46; 47; 48; 49; 50]. Geotechnical expertise should determine the possibility of constructional activity [48]. An overview of stability in the undermined areas is given in Figure 11.

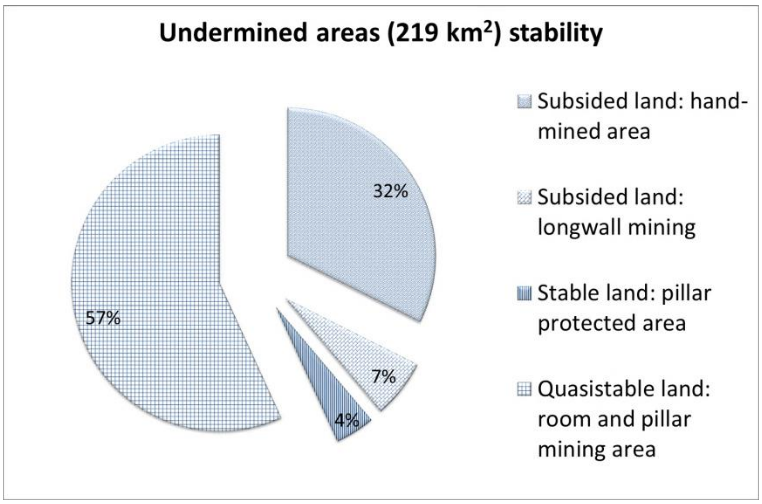

Figure 11 Used mining method and its relations to land stability

4.2. Groundwater

Groundwater accumulates in sedimentary rocks via cracks. Cracks in sedimentary rocks determine the main properties of the rock, such as hydraulic conductivity, permeability, specific storage and specific yield as well as the strength properties of rock [51]. The amount of water in cracks depends on the season. In active circulation belts the temperature of water depends mostly on air temperature, and the temperature of groundwater depends on geological conditions and bedding depth [51]. The quality of water in closed mines improves with time as the content of sulphates and iron in mine water decreases, gradually getting below the maximum level permitted for drinking water in about five years after mine closure [52].

Horizontal hydraulic conductivity of an aquifer, vertical hydraulic conductivity of an aquitard, aquifer ratio of vertical and horizontal hydraulic conductivity, rock-specific yield and artesian capacity of storing all these parameters depend on the material and layer thickness [53]. Permeability of a porous medium can be defined as the ease with which a fluid can flow through that medium. It depends on the physical properties of the porous medium - grain size, grain shape, arrangement and interconnection between pores. Water permeability is largely affected by the geological disturbance of the Earth crust, which makes the aquifer highly anisotropic [52]. The permeability of rock is determined by the size of the pores between rock particles [53, 54]. If the rock has small pores, water cannot infiltrate into the rock easily and this means that the rock is impermeable. On the other hand, if the rock has large pores, water infiltrates easily and thus the rock is permeable. When water flows through an area of impermeable rock, some amount of water still infiltrates in the ground. As a result there is a high surface runoff which leads to a high volume of water flow [55].

Water quality is also important, because sulphate content varies widely. The sulphate content in mines still filling with water after the closure is high whereas its content is low in closed mines [PAPER III; 56; 77]. Depression cones form around mining areas during pumping from underground mines. The quantity of pumped-out water from mines depends highly on the amount of precipitation and less on groundwater or water infiltrating from closed mines. According to performed measurements and calculations, precipitation accounts for up to 70% of the water pumped out of mines [52; 57]. If the hydraulic conductivity of the streambed is high, the cone of depression may extend only partway across the stream. But if the hydraulic conductivity of the streambed is low, the cone of depression may expand across and beyond the stream [53]. There are two water levels in the ground – dynamic and static water level. Dynamic water level is the level that forms during continuous pumping and static water level is the original natural water level.

4.2.1. Rock parameters

Moisture content is the ratio between the weight of water and the weight of solids in a sample. Degree of saturation is expressed by the saturation index which is the percentage of sample voids filled with water. Effective porosity is the volume of interconnected voids allowing free water flow divided by the total sample volume [53]. Effective porosity (Table 5), vertical and horizontal hydraulic conductivity (Table 6) and permeability are hydrogeological parameters that greatly depend on the size of sediment grains and the percentage of various sediment fractions. Porosity is given as the ratio of volume of voids to the total initial volume of a specimen before drying, which includes both voids and solids. For example, the average porosity of sandstone is 10%, with 35% for sands and 50% for clay [51; 54]. Generally, if the water content increases, the porosity increases, and the decrease of the water content is accompanied by the decrease in porosity.

Table 5 Representative porosity values for sedimentary rocks [53]

Rock type	**Porosity (%)**
Sandstone	14-49
Siltstone	21-41
Claystone	41-45
Shale	1-10
Limestone	7-56
Dolomite	19-33
Moraine	25-40

Table 6 Representative values for horizontal and vertical hydraulic conductivity [53]

Rock	**Horizontal hydraulic conductivity (m/s)**	**Vertical hydraulic conductivity (m/s)**
Gravel	$4.7x10^{-5}$ - $1.3x10^{-2}$	
Limestone	$9.4x10^{-9}$- $9.4x10^{-3}$	
Sand and gravel	$9.4x10^{-4}$ - $2.3x10^{-3}$	
Sandstone	$4.7x10^{-6}$ - $2.3x10^{-4}$	
clay	$9.4x10^{-6}$ - $9.4x10^{-7}$	$2.3x10^{-10}$- $4.7x10^{-9}$
shale	$4.7x10^{-12}$ - $4.7x10^{-8}$	$4.7x10^{-14}$ - $4.7x10^{-10}$
Clay, sand and gravel		$9.4x10^{-9}$ - $2.8x10^{-8}$
Sand, gravel and clay		$4.7x10^{-8}$ - $4.7x10^{-7}$

Hydraulic conductivity depends on properties of both the porous medium and the fluid. Hydraulic conductivity (K) is defined as the specific discharge of a porous medium under a unit hydraulic gradient – q=KI. Hydraulic gradient (I) is hydraulic head loss per distance – I=dh/dl. Horizontal conductivity is mostly

10-100 times higher than vertical conductivity in stratified deposit [58]. Specific storage (Ss) is the volume of water released from storage from a unit volume of aquifer per unit decline in hydraulic head. Specific yield (Sy) is volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table (Table 7). Specific yield is a dimensionless value [53]. Transmissivity (T) is the product of hydraulic conductivity and saturated thickness – T=Kb.

Table 7 Specific water yield of common rocks [53]

Material	**Specific Yield (%)**
Silt	20
Clay	6
Limestone	14
Gravel, coarse	21
Gravel, medium	24
Gravel, fine	28
Sand, coarse	30
Sand, medium	32
Sand, fine	33
Sandstone, fine grained	21
Sandstone, medium grained	27

All these properties (Table 5; Table 6; Table 7) are not the same in the mined out area. They can be used in accordance with the applied mining method (Figure 12; Figure 13) and therefore the knowledge of mining technology is essential [PAPER VI; 80].

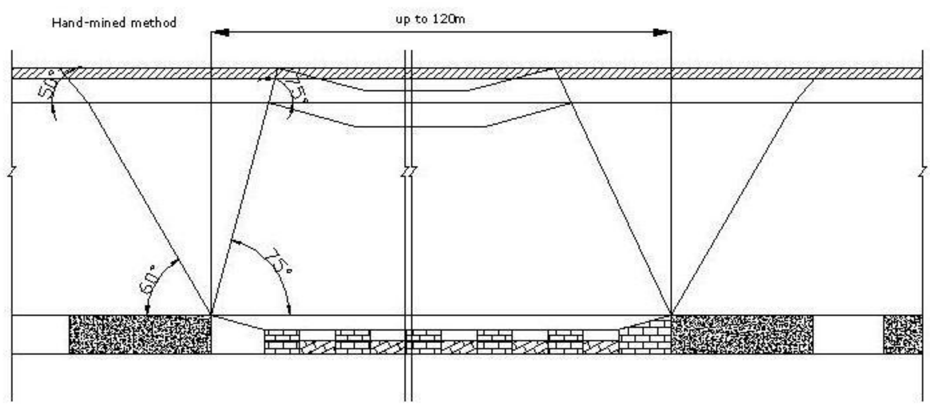

Figure 12 Cross section of hand mining technology [PAPER VI; 80]

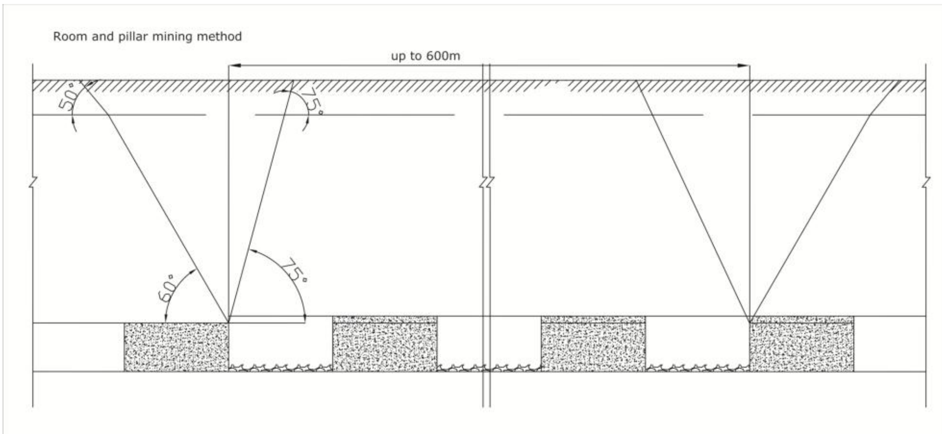

Figure 13 Cross section of room and pillar mining method [PAPER VI; 80]

The basis for the geometric model, groundwater model and subsidence model was constructed as the result of mapping, modelling and simulating. The geometric model shows higher storage in underground abandoned mining area where water flows towards the wings of the oil shale deposit. Water level has recently risen in the central northern part [PAPER V; 79].

4.3. Geometric properties of the water body

Geometric parameters for the model are: oil shale seam bottom elevation; roof height; length, width and height of pillars and workings in the mines; and thickness of overburden that is divided into required number of sublayers by different storativity values. The main tools chosen for spatial modelling were spreadsheets and MS Access databases for systemising and querying the data, MapInfo for georeferencing, Vertical Mapper for interpolating and grid calculations and Modflow for pumping simulation. Layer thicknesses and required properties were calculated with the help of interpolated grids and surface elevations (Figure 14). Modelled results show that the flat oil shale layer bottom slopes towards south (Figure 15). Geological fault zones are visible (rapid changes in elevation) (Figure 15).

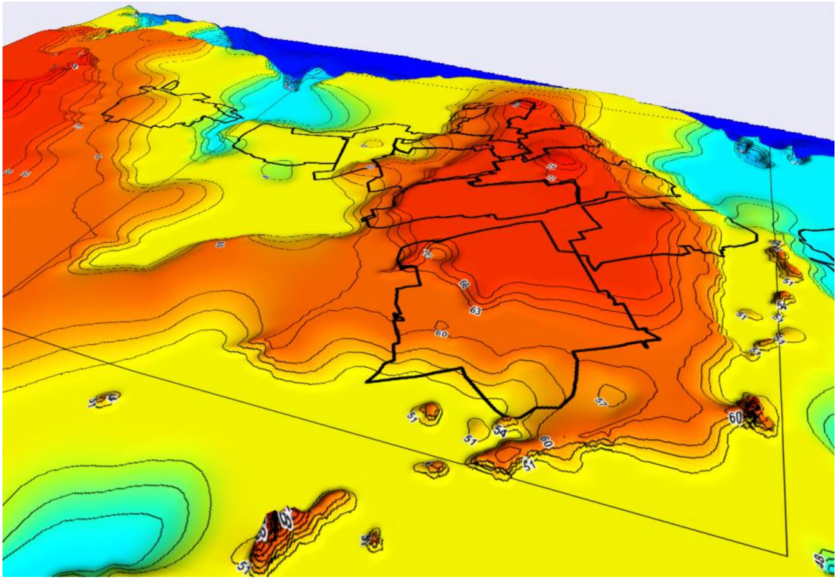

Figure 14 Ground surface of the study area

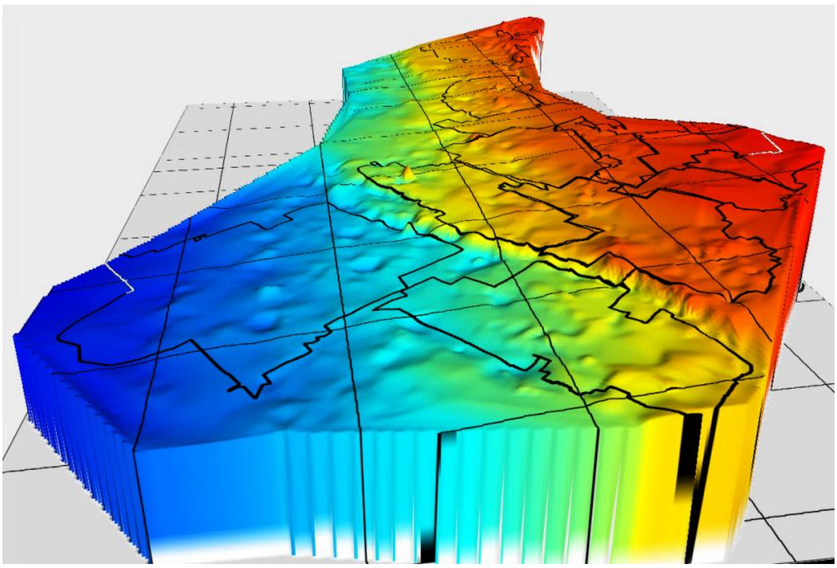

Figure 15 The oil shale layer is flat and descends 3 meters per kilometre

4.4. Hydrological properties of the water body

After grid calculation, the initial data for the base model shows the average thickness of oil shale 2.5 m which varies from 1.5 to 3.2 meters. The thickness of overlaying rocks varies from 6 to 66 meters (Table 8).

Since hydrogeological situation has changed relatively fast due to closing down of several mining operations and stopping of pumping in these regions, a dynamic model has to be created which simulates the groundwater level, amount of water in working and abandoned underground mines and potential productivity of wells starting to operate for energy extraction [59]. The main hydrogeological parameters for the hydrogeological model are porosity, vertical and horizontal hydraulic conductivity, infiltration rate, storage and information about water aquifers. The dynamic model must be checked with a spreadsheet as well as the amount of water found in the study area, using the same input parameters as in the hydrogeological ModFlow model (Table 9; Figure 16).

Table 8 Data on mines within the study area, thicknesses of oil shale and overburden layers and surface elevation

Mine	Overburden thickness, m			Oil shale thickness, m			Ground surface, m		
	min	avg	max	min	avg	max	min	avg	max
Tammiku	11	23	43	2.8	2.8	2.8	50.0	67.4	80.0
Kukruse	9	11	12	2.8	2.8	2.9	59.9	70.5	79.5
Mine no. 2	9	13	22	2.8	2.8	2.8	58.2	70.0	75.9
Mine no. 4	4	12	20	2.8	2.8	2.8	49.9	61.7	72.5
Sompa	12	23	34	2.7	2.8	2.8	50.0	62.1	71.5
Viru	32	42	50	2.7	2.8	2.8	57.0	69.4	72.0
Estonia	49	57	66	2.6	2.7	2.8	50.0	63.4	70.0
Kohtla	3	15	54	2.7	2.8	2.8	49.8	51.1	60.0
Käva 1	15	21	30	2.8	2.8	2.8	51.8	59.5	62.0
Käva 2	7	10	13	2.8	2.8	2.8	58.9	66.1	77.8
Ahtme	13	37	55	2.8	2.8	2.8	42.3	63.8	71.2
Mine	Water level year 2000, m			Water level year 2004, m			Water level year 2008, m		
	min	avg	max	min	avg	max	min	avg	max
Tammiku	25.1	35.4	41.8	34.9	47.8	51.1	28.2	45.0	47.4
Kukruse	51.0	52.1	53.9	49.4	50.0	50.1	51.2	52.1	57.7
Mine no. 2	39.2	45.9	51.8	49.2	50.0	51.5	42.6	46.8	51.9
Mine no. 4	21.0	39.2	47.5	40.9	42.0	49.7	41.0	42.5	47.8
Sompa	19.8	22.6	38.7	41.4	42.0	45.0	32.6	41.8	45.0
Viru	11.5	24.0	37.0	17.3	26.4	50.0	11.3	24.6	44.8
Estonia	-15.0	1.0	52.2	-18.5	-0.8	25.6	-15.1	0.6	41.5
Kohtla	22.2	34.9	44.2	37.8	41.6	44.4	30.8	40.7	47.5
Käva 1	49.4	51.4	53.3	49.7	50.0	50.5	50.5	51.5	52.1
Käva 2	40.8	51.3	52.7	43.8	50.0	50.8	43.2	51.3	52.4
Ahtme	7.8	20.5	34.8	18.1	26.8	28.6	19.4	42.0	45.1

Table 9 Parameters for a hydrogeological model in ModFlow

Seam	Specific storage	Specific yield	Effective porosity	Total porosity	Conductivities		
	Ss, 1/m	Sy			Kx (m/d)	Ky (m/d)	Kz (m/d)
Quaternary	4.5	0.14	0.045	0.14	15	15	1.5
Limestone overburden up to 20m	1.5	0.14	0.015	0.45	30	30	3
Limestone overburden 20m and deeper	1	0.12	0.1	0.3	8	8	1
Not mined area (defaults)	1	0.12	0.01	0.3	25	25	2.5
Kukruse mined area	5	0.67	0.05	0.25	300	300	30
Käva 2 mined area	5	0.67	0.05	0.25	300	300	30
Käva 1 mined area	5	0.67	0.05	0.25	300	300	30
Pavandu open cast mined area	5	0.25	0.05	0.25	100	100	10
Mine no 4 mined area	5	0.25	0.05	0.25	150	150	10
Kohtla mined area	5	0.11	0.05	0.25	150	150	10
Kohtla open cast mined area	5	0.25	0.05	0.25	80	80	8
Aidu open cast mined area	5	0.25	0.05	0.25	100	100	10
Sompa mined area	5	0.25	0.05	0.25	500	500	50
Mine no 2 mined area	5	0.25	0.05	0.25	200	200	20
Tammiku mined area	5	0.25	0.05	0.25	500	500	50
Ahtme mined area	5	0.25	0.05	0.25	500	500	50
Viru mined area	10	0.3	0.1	0.3	1000	1000	100
Estonia mined area	10	0.3	0.1	0.3	1000	1000	100
Limestone of oil shale bottom	1	0.12	0.1	0.3	10	10	1
Aquitard at bottom of limestone					10^{-6}	10^{-6}	10^{-7}

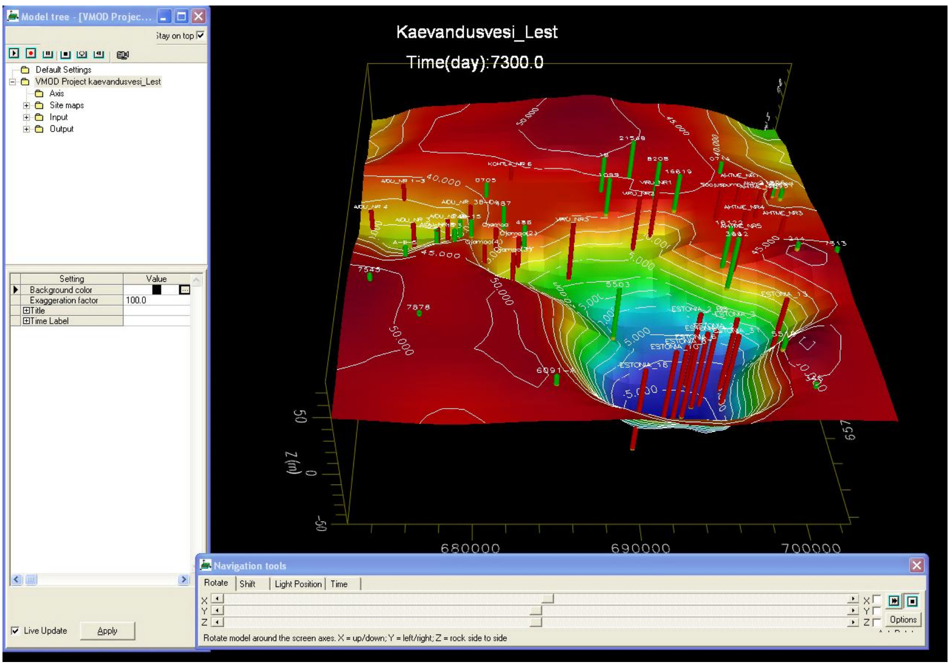

Figure 16 A screen shot of the dynamic mine water flow model

5. Mine water as a heat source

5.1. Heat source calculations

Heat can be defined as energy transferred between matters because of differences in temperature. The ability of a matter to transfer heat depends on its mass and temperature. In this study the primary analytical tools are spreadsheet models and GIS data analysis tools. Mines start filling up with groundwater as water pumping from the mines stops after their closure. Technological and hydrogeological modelling allows calculating the amount of water in the mines [57; 60]. Nevertheless, free flow in underground workings depends on subsidence and closing practice in mines and needs to be checked by pumping tests. Groundwater and underground pool water can be used as a heat source for a heat pump complex.

Groundwater: In areas where groundwater is abundant and easily accessible, it is extracted from a well and circulated through the cold side of the heat pump. Groundwater can be used either directly via circulation through the evaporator or indirectly via the use of an intermediate heat exchanger. An intermediate heat exchanger is the preferred choice in most cases, as groundwater may cause corrosion or clogging of the evaporator. After leaving the heat exchanger, the cold ground water is directed back into the ground via an injection well.

Underground pool water: The water in underground mines has a stable temperature all year. Subjected to a heat pump and returned back, the water heats up when mixed with warmer water and heat of the earth.

The areas, underground workings or outflows where energy could be extracted can be called energy spots. To locate the energy spots the limiting factors should be taken into account and a spatial query applied. The limiting factors include water protection and environmental protection areas, communication, restricted zones and areas, and other objects [PAPER II; PAPER III; PAPER VI; 61; 76; 77; 80].

The following equation can be used to calculate the transfer of heat energy:

$$Q = m \cdot c \cdot \Delta t \text{ (kW)} \qquad (1)$$

where:
Q – heat absorbed or released (kW)
m – water mass (kg/s);
c – specific heat capacity (4,19 kJ/kgK for water);
Δt – change in temperature (^{o}C)

To analyse the situation, the water volume for a heat pump has to be known in addition to the coefficient of performance (COP) and degrees of temperature to be decreased in the heat pump [62], where:

- Water volume for heat pump – amount of water that is pumped through a heat pump (m^3/h).
- Change in temperature – depends on the quantity of the heat extracted from water (^oC)
- Coefficient of performance (COP) – depends on electricity consumption of the heat pump complex
- Water volume and change in temperature are inter-dependent. If the water is returned back to mine, it can quickly heat up in the ground, and its reheating speed depends on concrete technological solutions.

COP is a ratio of energy output to energy input. A COP of 2 means that the heat pump can produce twice as much heat as it takes in to work, discounting small expenditures in its motor. Normal heat pumps have COPs that range between 2 and 5, depending on their efficiency. In order to know how much electricity is needed to get heat with a heat pump, we have to know the COP and then calculate the electricity need with the equation:

$$COP = \frac{Q_{heat\,out}}{Q_{electric\,in}} \qquad (2)$$

where:
COP – coefficient of performance;
$Q_{heat\ out}$ – quantity of heat production by heat pump (kW);
$Q_{electric\ in}$ – quantity of electricity for heat production (kW).

In the current study of underground water pools potential the usage of heat pumps is analysed with the coefficient of performance of three (COP = 3).

6. Results

6.1. Subsided land and collapses

Previous studies and theoretical background defined the maximum subsidence that may occur [63; 64]. These studies were carried out when modern technological facilities were not yet available. There are many new technological solutions for assessment of undermined land such as 3D scanning and LIDAR. Using aerial photographs and altitude data (known as LIDAR data), it has been found out that the longwall areas have sunk less than predicted. On the basis of the analysis of longwall subsidence it can be said that the land subsidence is 0.50-0.70 m as compared to the theoretical estimates of 0.90 m. Such subsidence encourages the formation of wetlands as water fills old mine shafts in the originally marshy area.

6.2. Amount of mine water in undermined areas

The amount of water in different seams was calculated using a spreadsheet model. Water amount in the top layers of oil shale was estimated taking into account porosity and thickness of seams. Applied mining technology and thickness of oil shale layer determine the free space in a certain mine to be filled with mine water (Table 10). The amount of water in the extracted oil shale layer was calculated considering these factors (Table 10). The results of the calculations show that the amount of water is highest in the Ahtme mine (Figure 17; Table 10). Most of the water located in the mining areas is found in the extracted oil shale seam (Figure 18; Table 10).

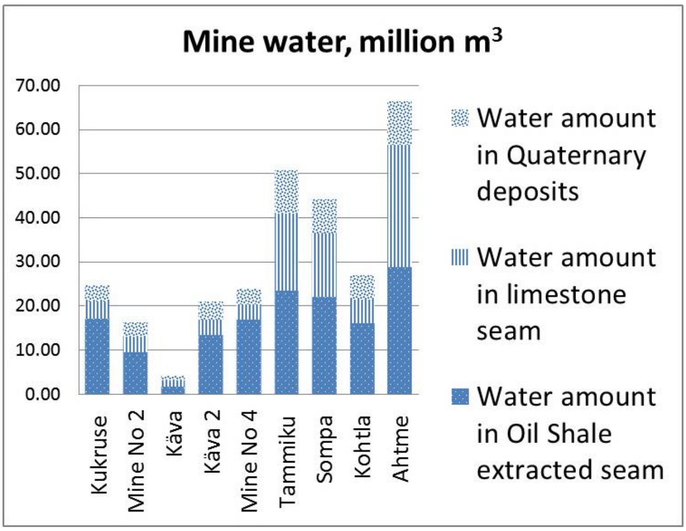

Figure 17 Amount of mine water in different mines

Table 10 Amount of mine water in study area

Options	Kukruse	Mine No 2	Käva	Käva 2	Mine No 4	Tammiku	Sompa	Kohtla	Ahtme
Mined oil shale seam thickness, m									
Hand-mined face	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Hand- mined rooms	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Room and pillar	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Drifts	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Longwall face	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Mined field area, km^2									
Hand-mined face	11.28	6.87		9.16	7.71	4.36	12.70	3.80	6.33
Hand- mined rooms	3.50	0.00	1.84	1.73	0	0	0.06	1.36	0.05
Room and pillar	0.29	1.70		0.79	1.08	11.81	1.86	0.55	19.22
Drifts	0.06	0.00	0.00	0.04	0.69	0.36	0.00	0.02	0.30
Longwall face	0	0		0	0.95	2.74	3.52	6.41	0.46
Total mined area	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36
Mine water amount, million m^3									
Water amount in Quaternary deposits	3.66	3.37	1.04	4.19	3.34	9.94	7.76	5.48	9.96
Water amount in limestone seam	3.94	3.40	1.37	3.56	3.47	17.32	14.46	5.30	27.61
Water amount in Oil Shale extracted seam	17.05	9.54	1.74	13.29	16.92	23.51	21.93	16.14	28.75
Total	**24.65**	**16.30**	**4.14**	**21.04**	**23.74**	**50.77**	**44.15**	**26.91**	**66.32**
Mine water amount distribution in seams, %									
Water amount in Quaternary deposits	14.8	20.7	25.0	19.9	14.1	19.6	17.6	20.4	15.0
Water amount in limestone seam	16.0	20.8	33.0	16.9	14.6	34.1	32.7	19.7	41.6
Water amount in Oil Shale extracted seam	69.2	58.5	42.0	63.2	71.3	46.3	49.7	60.0	43.3

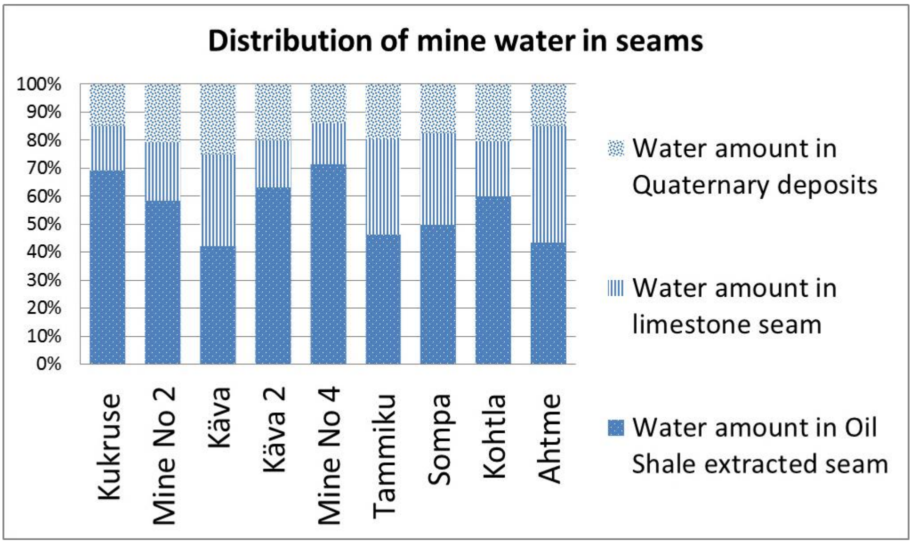

Figure 18 Relative amount of mine water in different seams

6.3. Water requirements for a heat pump

The criteria for site selection were: an existing heat pipe; presence of at least 5000 consumers; an additional heating option; large amount of mine water. Considering these criteria, the most favourable location of a heat pump complex is on top of the Ahtme oil shale mine (Figure 19) which is located near the Ahtme thermal power plant. The heat pump complex can use the Ahtme underground water pool for heat production. The amount of mine water in the Ahtme mine is 69 million m^3. The heat consumption is 10 MW in summer period and 50 MW in winter period. Knowing the required heating capacity and using Equation 1, a spreadsheet model is used for calculating the necessary water requirements for a heat pump (Table 11).

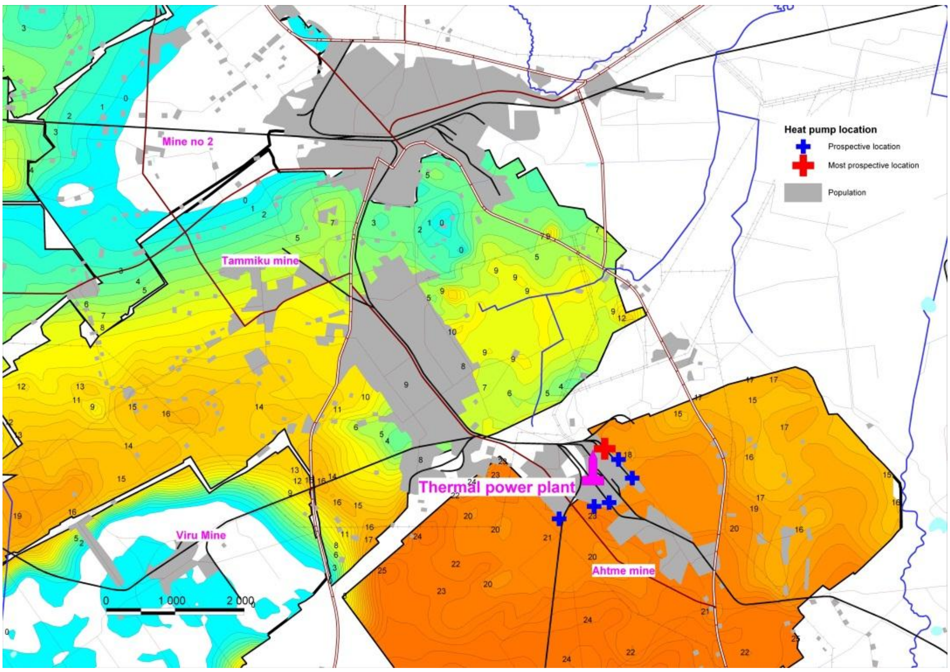

Figure 19 Prospective locations for a heat pump in Jõhvi and Ahtme area, numbers show the water pressure from the bottom of the oil shale seam

Table 11 Requirements for water depend on heat production and temperature reduction

Heat requirement, MW	**Change in temperature , ^{O}C**	**Initial water temperature, ^{O}C**	**Final water temperature after heat pump, ^{O}C**	**Water requirement, m^3/h**
10	1	8	7	8 604
10	2	8	6	4 302
10	3	8	5	2 868
10	4	8	4	2 151
50	1	8	7	43 021
50	2	8	6	21 511
50	3	8	5	14 340
50	4	8	4	10 755

6.4. Technological solutions for using a heat pump complex

Using mine water in heat pumps must comply with environmental protection requirements and the best possible technical solution in this case is pumping the water through a drillhole onto the ground surface (Figure 20) [PAPER VI; 65; 66; 80]. After lowering the temperature of mine water in the heat pump for about 1 to 4 degrees, it is directed back to the mine or to the water source. If we use water from underground pools, the recommended temperature reduction must be at least four degrees. If the temperature is lowered less, larger volumes of mine water are needed (Table 11). A heat pump complex, which produces 10 MW of heat, uses 2151 m^3/h mine water, produces 87 650 MWh heat per year and consumes 29 217 MWh of electricity (COP =3). A heat pump complex, which produces 50 MW of heat, uses 10 755 m^3/h mine water.

The best possible solution is to build a 10 MW heat pump complex which allows optimal heat production throughout the year. In addition, it is necessary to use a thermal power plant for heat production during the winter season. The best location for the heat pump is near the Ahtme thermal power plant. The potential locations are shown in figure (Figure 19) where it is possible to use the existing district heating network and, if needed, increase the temperature in the heating network using the thermal power plant.

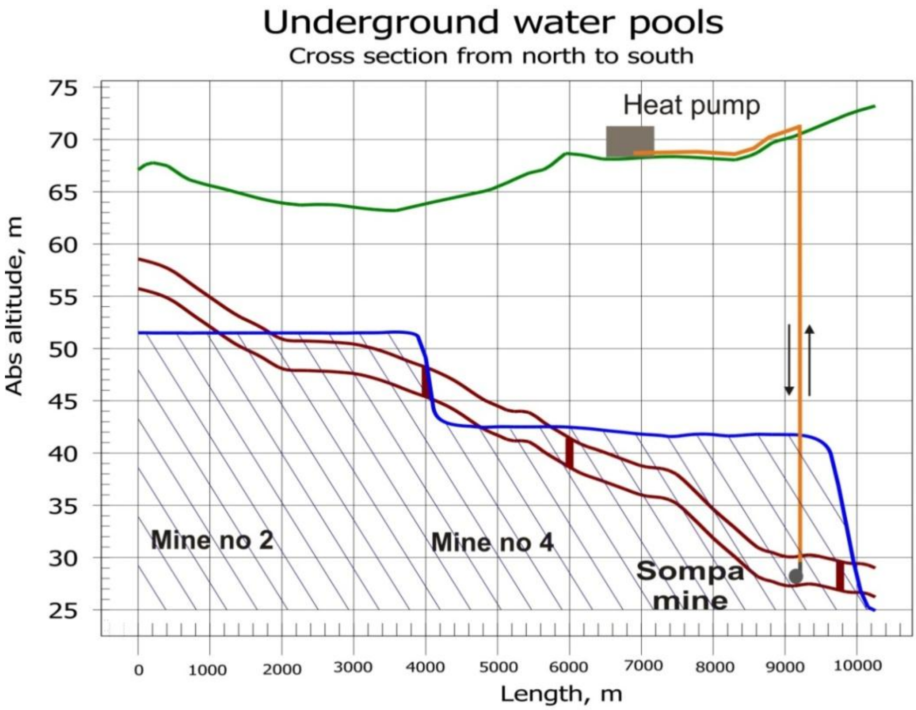

Figure 20 North-south cross section of the underground mining area and an example of a heat pump installation [PAPER VI; 80]. Top layer – ground surface; two parallel lines – determine the oil shale seam; hatched area – determine the measured and interpolated groundwater level; vertical line – mine water movement

6.5. Heat pump calculations and COP

The best possible technical solution for usage of mine water in heat pumps in Ahtme is to:

1) pump the water through a drillhole onto the ground surface
2) direct the water to a heat exchanger unit
3) lower mine water temperature in the heat exchanger of the heat pump about 1-4 degrees,
4) direct the mine water back to the mine

If we use water from underground water pools, the recommended temperature reduction must be more than one degree, which depends on the efficiency of the heat exchanger. If the temperature is lowered less, larger volumes of mine water are needed.

The heat pump complex in Ahtme will need water pumps as well as heat pumps. Possible pump parameters are shown in the Table 12. Water requirement and COP values for usage of these pumps are shown in Table 12. In the Kiikla settlement the installed heat pump is operating as a pilot unit exploiting mine water as a heat source. The COP values and other parameters for Kiikla are shown in Table 14.

Table 12 Water pumps for a heat pump complex

Pumping station

Producer	Pleuger pumps	Unit
Capacity	1200	m^3/h
Head	34	m
Motor output	165	kW

Heat pump station

Producer	Acwell	Unit
Heating capacity	1536	kW
Power input	366	kW

Table 13 COP values for the Ahtme 10MW and Ahtme 50MW heat pump complex

Ahtme 10MW

ΔT	Heat production, kW	Water needed, m^3	Pumps needed	Electricity for pumps, kW	Heat pumps needed	Electricity for heat pumps, kW	Total electrycity consumption, kW	COP
1	10000	8592	8	1 320	7	2 562	3 882	2.58
2	10000	4296	4	660	7	2 562	3 222	3.10
3	10000	2864	3	495	7	2 562	3 057	3.27
4	10000	2148	2	330	7	2 562	2 892	3.46

Ahtme 50MW

ΔT	Heat production, kW	Water needed, m^3	Pumps needed	Electricity for pumps, kW	Heat pumps needed	Electricity for heat pumps, kW	Total electrycity consumption, kW	COP
1	50000	42959	36	5 940	33	12 078	18 018	2.78
2	50000	21480	18	2 970	33	12 078	15 048	3.32
3	50000	14320	12	1 980	33	12 078	14 058	3.56
4	50000	10740	9	1 485	33	12 078	13 563	3.69

Table 14 The Kiikla 500kW heat pump [67]

Pilot project in Kiikla 500kW heat production unit

Date	Heat production, MWh	Elecricity for heat pump, kWh	Electricity for pumps, kWh	Total electrycity consumption, kW	Pumped amount of water, m^3	Water from mine, °C	Water to mine, °C	ΔT	COP
14.04.2011	3.909	1622		1622	1841	6.0	5.0	1.0	2.41
18.04.2011	14.122	5929		5929	7396	6.1	5.4	0.7	2.38
19.04.2011	2.594	1201	7867	9068	1807				0.29
20.04.2011	3.559	1415	341	1756	1488	6.4	5.7	0.7	2.03
21.04.2011	2.104	655	268	923	1534	6.1	4.9	1.2	2.28
25.04.2011	8.381	2749	1245	3994	6852	6.4	5.1	1.3	2.10
27.04.2011	3.355	1108	542	1650	3094	5.8	4.8	1.0	2.03
29.04.2011	3.321	1131	632	1763	3151	5.9	4.6	1.3	1.88
2.05.2011	6.970	2421	893	3314	4671	6.2	5.2	1.0	2.10
4.05.2011	4.954	1743	558	2301	2856	6.1	5.2	0.9	2.15
6.05.2011	4.820	1649	599	2248	2978	6.6	5.2	1.4	2.14
9.05.2011	5.175	1669	877	2546	4317				2.03
30.09.2011		881	873	1754					0.00
18.10.2011	45.684	15600	3468	19068	24673				2.40
27.10.2011	29.015	9671	1800	11471	10498				2.53
31.10.2011	11.828	4299	842	5141	4753				2.30
8.11.2011	20.068	6081	1538	7619	8688				2.63

7. Discussion

The obtained results are very important because of the existing plans to close the Aidu open cast and the Viru underground mine in 2014. Pumping in these mining sites will stop and the mining fields start filling with mine water. Shutting these mining fields will also change water regime in the region and new potential places for using mine water as a heat source for heat pumps can be found. However, heat collection from mine water can be carried out using other methods. Instead of pumping the mine water through the heat exchanger of a heat pump it is expedient to establish an underground net for heat collection if the drifts are still dry, which enables us to use the mine water heat more effectively.

Thanks to the characteristics of Estonian oil shale deposit structure where interlayers (limestone) strongly differ in properties from oil shale, its raw material is easily separated by gravitational methods. Run of mine (ROM) is preliminary selectively crushed, screened and then sent to the dense-media suspension. After the screening, part of the material is sent for the separation of fine grain with high heating value [68; 69; 70]. The investigation produced the results that the principal possibility for increasing the heating value of energetic oil shale is enrichment of fine grain oil shale in hydrocyclones, pneumatic separators and settling centrifuges [71; 72].

The result of oil shale enrichment depends on the preliminary underground processing of ROM: the more limestone is left underground the more fine grain oil shale there is and the importance of its enrichment in the separator increases. The growing amount of fine grain oil shale, in its turn, increases the quantity of limestone taking up the underground space and leaving less room for mine water. Thus in future the applied oil shale mining technology will determine the free space in mined areas and the potential of mine water usage as a heat source for heat pump complexes [PAPER IX; 73]. The selection of technology directly depends on economic considerations, but, if economic issues are set aside, then the best available technology (BAT) criteria have to be used [PAPER VIII; 82; 73; 74].

There is Kose settlement located near the Ahtme mine water outflow to the Sanniku stream. The distance between the settlement and the outflow is 500 m. The Ahtme outflow works all-year-round and it is worthwhile for the future to set up a heat pump complex there to produce heat for Kose settlement. It must be taken into account that the amount of mine water flowing out from the Ahtme mine is related to rainfall.

8. Conclusion

In Estonia, more than 90% of electricity is produced from oil shale which has been mined for over 90 years with the total production exceeding one billion tonnes. The oil shale is mined in two ways: underground (room and pillar mining method) and surface (open cast mining method). Application of underground mining of oil shale created underground free space and, as it had been mined below the groundwater level, the workings filled with water after their closure.

The subject of this thesis became topical many years ago and many research projects funded by research organizations as well as by private companies were carried out. The aforementioned projects dealt mainly with the research of two subjects: stability of undermined areas and mine water balance. Filled underground oil shale mines create underground water pools called technogenic water bodies which have a stable temperature all the year round but are not yet exploited as a heat source for heat pumps and for reduction of winter-time heating costs. In order to use mine water as a heat source for heat pumps the relation between applied mining technologies, underground space, hydrogeological parameters for closed or abandoned mines and subsidences has to be found. At present these relations are unknown. The aim of this research is to find these relations and offer solutions for usage of undermined areas.

An oil shale block model has been created with the help of topographic and geological data (stratigraphy, hydrogeology, LIDAR data). It describes the parameters of mining conditions i.e. geological, technological and environmental conditions that directly affect the oil shale mining. The most common of them are oil shale layer thickness, depth, angle, rock stability, etc. The oil shale block model shows the top layers: the surface, layers of limestone, oil shale seam and ground water levels.

There are many new technologies to use in assessment of undermined land such as 3D scanning and LIDAR. Using the aerial photograph and altitude data (known as LIDAR data) it has been found out that the longwall areas have sunk less than predicted. It is not possible to give general recommendations and permissions for building, road construction or other land usage as every specific case has to be solved separately, depending on the mining conditions and method.

The areas, underground workings or outflows where it is possible to extract energy can be called energy spots. To locate the energy spots the limiting factors of water protection, environmental protection areas, techno-communication, restricted zones, areas and objects should be taken into account and a spatial query applied. Most of the water located in the mining area is found in the extracted oil shale seam (Figure 18; Table 10) and can be exploited as a heat source for heat pumps.

The best possible technical solution for using mine water in heat pumps is to pump the water through a drillhole onto the ground surface (Figure 20). After lowering the temperature of mine water in the heat pump about 1-4 degrees, it is directed back to the mine or the water source. If we use the water from underground pools, the recommended temperature reduction must be at least four degrees. If the temperature is lowered less, larger volumes of mine water have to be consumed which would change the land and pillar stability situation in the mine.

The obtained results are very important, because there are plans to close the Aidu open cast and Viru underground mine in 2014. Pumping in the mining sites will stop and the mining fields start filling with mine water. Closing of these mining fields will also change the water regime in the region. New potential places for using mine water as a heat source for heat pumps will be found. It is also possible to carry out heat collection from mine water using a different method: instead of pumping the mine water through the heat exchanger of a heat pump it is expedient to establish an underground net for heat collection if the drifts are still dry.

Selection of the technology depends directly on economic considerations, but, if economic issues are set aside, then the BAT criteria have to be used. In future the oil shale mining technology will determine the free space in mined areas as well as the potential usage of mine water as a heat source for heat pump complexes.

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Kokkuvõte

Altkaevandatud alade kasutamine Eesti põlevkivimaardlas

Põlevkivi on Eestis kaevandatud enam kui 90 aastat. Selle aja jooksul on maa alt välja veetud enam kui üks miljard tonni põlevkivi, lisaks põlevkivile veel põlevkivikihindi lubjakivikihid – neist on moodustunud aheraine mäed, mis nüüd ilmestavad Ida-Virumaa loodust. Kui kaevanduses enam ei ole võimalik põlevkivi kaevandada (tehnoloogiliselt, varu ammendumisel või majanduslikult), siis see suletakse vastavalt kehtestatud korrale. Eesti põlevkivimaardlas on suletud tänaseks maardla keskosas kümme kaevandust, viimased neist suleti 1999…2002 (Sompa, Tammiku, Ahtme ja Kohtla kaevandus).

Põlevkivi kihind asub enamasti põhjaveetasemest allpool. Põlevkivi kaevandamiseks tuleb alandada põhjaveetaset. Nii on tekkinud Ida-Virumaale põhjavee alanduslehter. Kaevandamise lõppedes kaevandusest ja karjäärist vee välja pumpamine lõpetatakse ja põhjaveetase hakkab taastuma kaevandamise eelsele tasemele. Nii täituvadki suletud kaevandused ja karjäärid veega. Eesti põlevkivimaardlas on suletud kaevandustest veega täielikult täitunud Ahtme, Tammiku, Sompa ning osaliselt täitunud kaevandus nr 4, kaevandus nr 2, Käva, Käva 2, Kohtla, Kiviõli ning Kukruse.

Suletud põlevkivikaevanduste vee kasutamine soojusenergia või kineetilise energia allikana on üks võimalusi moodustunud tehnogeense veekogumi otstarbekaks kasutamiseks. Veekogumi kasutamise hindamiseks tuleb arvutada võimalik vee maht, vee vooluhulk ja analüüsida võimalikke kohti veevõtuks, vee pumpamiseks või soojuspumba paigutamiseks. Analüüsiks on otstarbekas koostada mäenduslik geoinfosüsteemi mudel, milles sisaldub kivimikihtide ja maapinna geomeetriline mudel, kaevanduse tehnoloogiline ruumiline mudel ja vee voolu hüdrogeoloogiline dünaamiline mudel. Mudeli abil simuleeritakse vee pumpamist soovitavatest kohtadest. Kaevandusvee kasutamise potentsiaal on just Ida-Virumaa valdades, seal asuvad suletud põlevkivi kaevandused. Samuti tuleb hoolikalt planeerida selles piirkonnas ehitustegevust altkaevandatud aladel.

Ida-Virumaad hõlmavates uuringutes on koostatud ühine uuringuala, kus asuvad töötavad ja suletud põlevkivikaevandused. Kaevandusvee kasutamist hõlmava uuringu tulemusena koostati kaevandusvee kasutamise potentsiaali kaart, mis baseerub veesamba survel ehk mida kõrgem sammas, seda potentsiaalsem on sellesse kohta rajada soojuspump, mis kasutaks kaevandusvett soojusallikana. Analüüsides veel olemasolevat soojustrasside olemasolu võib öelda, et suurtarbijana on kõige potentsiaalsem rajada soojuspumpjaam Ahtme soojuselektrijaama juurde. Optimaalseimaks soojuspumba võimsuseks oleks 10MW. See tagaks aastaringse sooja kraanivee olemasolu ning talvel saab kasutada Ahtme soojuselektrijaama vee temperatuuri tõstmiseks soovitud temperatuurini kui soojuspump ise seda ei võimalda, sest soojustrassis ringleva veetemperatuur oleneb suuresti välistemperatuurist.

Mäetaguse valla initsiatiivil rajati kaevandusveel baseeruv soojuspumpjaam Ida-Virumaale, Kiikla asulasse, mis paikneb Mäetaguse valla lääneosas. Asula ümbrusesse jäävad suletud Sompa kaevandus, hetkel veel töötav Viru kaevandus ning Ojamaa kaevandus. Rajatud soojuspumpjaam kasutab soojusallikana Sompa kaevanduses olevat kaevandusvett. Sompa kaevandus, mis jääb Kiikla asula kirdeossa, suleti 12.02.2000. Kaevandus piirneb põhjas endise kaevanduse nr 4 kaevandatud alaga, idas Tammiku, lõunas Viru ja läänes Ojamaa kaevandusega. Peale kaevanduse sulgemist hakkas kaevandus täituma veega, mille tase tasakaalustus paari aasta jooksul kõrgusmärgil 42…48 m (abs) vahel. Soojuspumpjaama võimsus on 500 kW, mis kasutab maksimaalselt 74 m^3/h kaevandusvett.

Võttes arvesse võimalikke piiranguid näeb Kiiklas rakendatud tehnoloogia ette, et kaevandusvesi pumbatakse maa peale, mööda torustikku juhitakse see soojuspumbani (umbes 1000 m), soojuspumba soojusvahetis alandatakse vee temperatuuri võimalusel kuni nelja kraadi võrra ning seejärel suunatakse mööda torustikku jahenenud vesi uuesti Sompa kaevanduse veebasseini tagasi, umbes 300 m kaugemale väljapumpamiskohast, nii jõuab tagasi suunatud vesi kaevanduses uuesti ülesse soojeneda. Torustik on rajatud külmumispiirist allapoole, et minimaliseerida talvise ilma mõju välja pumbatavale ning tagasi suunatavale kaevandusveele.

Suletud kaevanduste veetaseme stabiliseerimiseks on rajatud mitu väljavoolu. Neist suurimas Ahtme väljavoolus voolab kaevandusvesi aastaringselt Sanniku ojja. Väljavoolu läheduses asub Kose asula. Potentsiaalne on rajada soojuspump Sanniku oja lähedusse, mis aitaks kütta Kose asulat.

Eesti Energia Kaevandused AS lähimate aastate plaanid näevad ette Viru kaevanduse ja Aidu karjääri sulgemise. Seni veel kui kaevanduse käigud ei ole täitunud veega saab rajada maa alla soojuspumba jaoks soojakogumisekontuur. Kontuuri kasutades, jääb ära kaevandusvee pumpamine läbi soojuspumba soojusvaheti.

Abstract

Potential usage of underground mined areas in Estonian oil shale deposit

Underground oil shale mining has been applied for ninety years in Estonian deposit in the middle-north part of Baltic oil shale deposit. The underground mining method of oil shale creates underground free space and the mine workings fill with water after closing, which make the issues of land stability topical. It is not possible to give general recommendations and permissions for building, road construction or other land usage, as every specific case has to be solved separately, depending on the mining conditions and method.

Underground water pools or technogenic water bodies with all-year stable temperature emerge in the filled underground of oil shale mines. These water bodies have a potential use as a heat source for heat pumps and reduction of winter-time heating costs. The aim of this research is to calculate the amount of mine water in closed or abandoned oil shale mines in the central part of Estonian oil shale deposit and offer solutions for usage of undermined areas.

A 3D-model of the mined underground area has been created by applying geometric data from mine plans, acts of closed mines, borehole and land survey data. The main tools chosen for spatial modelling were spreadsheets and Microsoft Access databases for systemising and querying data, MapInfo Professional for georeferencing, Vertical Mapper for interpolating and grid calculations and MODFLOW for pumping simulation. Each step involved analysis and decision on what values to use to obtain the modelling results. Layer thicknesses and required properties were calculated with the help of interpolated grids and surface elevations.

Using mine water as a heat source for heat pump complexes is unique in the world. The first pilot pump in Estonia was launched in 2011 in Kiikla settlement. The best solution for such systems is a heat pump complex near the Ahtme power plant. The optimal size for the Ahtme heat pump is 10 MW heat production. Different methods of heat collection for heat pump plants can be applied when other mines are closed in future.

Curriculum Vitae

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Teenistuskäik

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Teadusorganisatsiooniline ja -administratiivne tegevus	2010 - ... Eesti Noorte Teadlaste Akadeemia, juhatuse liige
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Õppemetoodiline töö ja sellega seotud arendustegevus:
MGIS erinevate harjutuste juhendite koostamine.
Mäendustingimuste labori praktikumide juhendite koostamine ning arendamine.
Välitööde juhendamine ja läbiviimine.
Välitööde tulemuste presenteerimine veebikeskkonnas – juhend.

Mäenduse ja geoloogia teadusklubi töö organiseerimine. Teadusklubi on haridusliku taustaga ja mõeldud tudengite haridustee mitmekesistamiseks, et õppetöö ei koosneks vaid loengutes/harjutustundides käimises, vaid annaks lisaväärtust. Teadusklubi töös tehtud tegevused: teadusklubi seminaride läbiviimine, välitöögruppide vahel võistlusmomendi loomine (plakatid, aruanded, esitlused, veebilehed). Teadusklubi veebileht http://mi.ttu.ee/teadusklubi

Gümnaasiumi õpilastele kursuste ning loengute pidamine
- Geodisain- geoloogia, maavarad, majandus, Veebileht: http://mi.ttu.ee/geodisain
- TTÜ valikaine „Energeetika üldkursus“
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Auditoorne õppetöö
Sügissemester
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	2007, Veiko Karu; TTÜ arengufond: Mati Jostov'i nimeline stipendium
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	2006, Veiko Karu; Tänukiri TTÜ üliõpilastööde konkurss
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	2006, Veiko Karu; Eripreemia Eesti Mäeseltsilt. 2006.a tudengitööde konkursile esitatud artikli „Magneesiumiilmingutest põlevkivimaardlas” ning Mäenduse ja geoloogia teadusklubi juhtimine ning tegevuse korraldamise eest

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MIN-NOVATION. Kaevandamise ja kaevandamisjääkide ja jäätmete uuringud Eestis ja Läänemere piirkonnas

Põlevkivi kadudeta ja keskkonnasäästlik kaevandamine

Publikatsioonid

1.1. - 4 publikatsioon(i)

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1.3. - 1 publikatsioon(i)

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3.2. - 33 publikatsioon(i)

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Sabanov, S.; Reinsalu, E.; Valgma, I.; Karu, V. (2009). Mines Production Quality Control in Baltic Oil Shale Deposits. Valgma, I. (Toim.). Resource Reproducing, Low-wasted and Environmentally Protecting Technologies of Development of the Earth Interior (1 pp.). Tallinn: Department of Mining TUT; Russian University of People Friendship

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Curriculum Vitae

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	2004 - 2004 Eesti Põlevkivi AS: environment specialist`s help
	2003 - 2004 Tallinn children sportcenter: coach
	2002 - 2003 Viru Üksik-jalaväepataljon: military man
	2000 - 2002 Tallinn children sportcenter: coach
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Administrative responsibilities	2010 - ... Estonian Academy of Young Scientists, Board member
	2009 - ... European Council of doctoral candidates and young researchers: Eurodoc member delegate from Estonia
	2008 - ... Estonian Naturalists Society
	2008 - ... Estonian Naturalists Society: Geology Section Vice-Chairman
	2006 - ... Mining and geology science club
	2006 - ... Estonian Academy of Young Scientists
	2005 - ... Student council of the Faculty of Power Engineering
	2005 - ... Student Union Talveakademia
	2002 - ... Society of Mining Students
	2002 - ... The Geological Society of Estonia
	2002 - ... Estonian Mining Society
	2002 - ... Sport club "Sulgpalliklubi S-16"
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	2008 - 2009 Member of TUT Faculty of Power Engineering Curriculum

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	2007, Veiko Karu; Jaan Poska Scholarship
	2007, Veiko Karu; Mati Jostov Scholarship
	2007, Veiko Karu; Approbation, Mining Society
	2007, Veiko Karu; Accolade "Fieldis Studiosus"
	2007, Veiko Karu; Approbation, EMS, EGEOS, EGÜ Student work contest
	2006, Veiko Karu; Approbation, TUT Student work contest
	2006, Veiko Karu; Approbation, Ministry of Education and Research of Estonia
	2006, Veiko Karu; Approbation, Mining Society.
	2006, Veiko Karu; Attestation, Work health service and safeness
	2005, Veiko Karu; Certificate of Visual ModFlow
	2004, Veiko Karu; Approbation, Mining Society.
	2004, Veiko Karu; Student work contest : reward, Eesti Mäeselts (2004).Theme : About the geology of the "Polünotšnoe Mn shale"
Field of research	4. Natural Sciences and Engineering, 4.14. Industrial Engineering and Management(T340 Mining, 2.3. Other engineering sciences (sciences such as geodesy, industrial chemistry; metallurgy, mining))
	4. Natural Sciences and Engineering, 4.17. Energetic Research (T140 Energy research, 2.2. Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects])
	4. Natural Sciences and Engineering, 4.15. Construction and Municipal Engineering(T340 Mining, 2.1. Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects))
	4. Natural Sciences and Engineering, 4.1. Architecture and Industrial Design(P515 Geodesy, 2.1. Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects))

	4. Natural Sciences and Engineering, 4.13. Mechanical Engineering, Automation Technology and Manufacturing Technology(T120 Systems engineering, computer technology, 2.3. Other engineering sciences (sciences such as geodesy, industrial chemistry; metallurgy, mining))
	4. Natural Sciences and Engineering, 4.2. Geosciences(P420 Petrology, mineralogy, geochemistry, P430 Mineral deposits, economic geology, P470 Hydrogeology, geographical and geological engineering, P515 Geodesy, T250 Landscape design, T270 Environmental technology, pollution control, T340 Mining, 1.4. Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences))
	4. Natural Sciences and Engineering, 4.2. Geosciences, P470 Hydrogeology, geographical and geological engineering
	4. Natural Sciences and Engineering, 4.14. Industrial Engineering and Management, T340 Mining
	4. Natural Sciences and Engineering, 4.15. Construction and Municipal Engineering, T140 Energy research
	4. Natural Sciences and Engineering, 4.15. Construction and Municipal Engineering, T340 Mining
	4. Natural Sciences and Engineering, 4.13. Mechanical Engineering, Automation Technology and Manufacturing Technology, T120 Systems engineering, computer technology
	4. Natural Sciences and Engineering, 4.17. Energetic Research, T140 Energy research
	4. Natural Sciences and Engineering, 4.1. Architecture and Industrial Design, P515 Geodesy
Current grants & projects	Backfilling and waste management in Estonian oil shale industry
	MIN-NOVATION. Mining and Mineral Processing Innovation Network
	Sustainable and environmentally acceptable Oil shale mining

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3.2. - 33publications

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10. Appendixes

PAPER I **Karu, V**.; Västrik, A.; Valgma, I. (2008). Application of modelling tools in Estonian oil shale mining area. Oil Shale, Volume 25(2S), p. 134-144.

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APPLICATION OF MODELLING TOOLS IN ESTONIAN OIL SHALE MINING AREA

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The research needed for sustainable mining should be performed in nature, but large-scale tests are complicated. These studies are performed by computer modelling. The main task for modelling is to find suitable criteria and demonstration ways.

Modelling is a relatively new approach for planning new mines and analysing abandoned ones. Modelling itself is a convenient way for choosing, selecting and visualising the results, but deciding about optimal modelling methods and software is a complicated task. There are three main tasks of modelling to solve: mining technology, planning and development of mining and impact of mining.

Introduction

There are problems in composing development plans for industrial extraction of minerals (oil shale and building minerals, limestone, sand, gravel, clay, peat) at the level of both local authorities and country. There is no suitable methodology convenient for all parties as for criteria and skills for using natural resources – minerals, water, ground and forest.

The reserves of mineral resources have been analysed and calculated by Mining Department of Tallinn University of Technology [1]. Although we have worked out the best available technologies (BAT) and established proper mining conditions, limitations, infrastructure and economic background, the solutions which could satisfy all parties have still not been found.

Economy needs mineral resources and groundwater. Mining of mineral resources affects the environment, earth crust and landscape. The ownership of properties and claims can be changed during this process. All this will raise opposition of the society.

The changed earth crust and landscape could be even more valuable than the original one. It has been proved that the skilled operations may improve

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the state of the forest, water body and agricultural land in the mined area. Such an approach forms the basis for sustainable, environmentally friendly mining. The research needed for sustainable mining should be performed in nature, but performing large-scale tests is complicated. It is the world standard that these studies are performed by computer modelling. The main task at modelling is to find suitable criteria and demonstration ways.

Planning offices use different software for that purpose, but the following remarks have to be taken into account:

- the databases from different periods and of different structure are difficult to operate;
- the software to model ore and coal mining is complicated and expensive for flat-laying deposits like in Estonia;
- most of mining software programs are not suitable for solving environmental problems like those in Estonian deposits;
- software concerning mining problems in conservative industry is being developed everywhere. Estonian experience (shallow bedding, abundance of water, environmentally sensitive conditions) based on industrial tests and corresponding software applications will help to develop these systems for other regions.

Methods

There are several mining software programs. They are either freeware (different viewers), independent (GEMCOM Surpac and Minex, MapInfo, AutoCAD, ESRI, etc.) or additional (Discover, Map X, etc.) programs. Besides, it is possible to use online software programs (EduMine etc.). There are problems with the compatibility of the projects, because there are so many different software programs, and institutions use different software systems. Development of co-operation brings about difficulties in connection and transition of data. A problem like this poses an economical problem – the designers have to have as much different software as possible for the co-operation to work [2].

A method and a computer program have been developed to assess the underground-mined area of the oil shale deposit and to describe the range of the impact influence of mining operations. The program enables to evaluate the condition of the ground and, considering possible risks, to plan the usage of the ground and corresponding constructional actions. Using the geological dataset, the plan of mining operations and subsidences which are affected by mine work, it is possible to calculate the types of mine impact: formation of quasistable land, subsided land [3]. Binding the datasets enables to get a more detailed information than ever before about a certain territory.

A more environmentally friendly excavation is possible by using a continuous miner. There is no need for drilling and blasting operations, which cause a lot of vibrations in the ground and emission of dust. Excavating with a continuous miner produces less dust and vibrations.

Optimal mining software package for oil shale

The staff of the laboratory of mining design and planning applies mining software systems, tests and develops them in both research and teaching processes. The laboratory possesses software, databases, methods, hardware with necessary equipment (scanners, printers, plotters, savers, presenters, servers) all listed in Website http://mi.ttu.ee/mgislabor.

The following software used worldwide to model mining operations has been set up in the laboratory:

1. Gemcom Minex – modelling of stratified deposits;
2. Gemcom Surpac – modelling of mining processing and workings;
3. Visual ModFlow; AquaChem – modelling of groundwater flow and quality;
4. MapInfo Professional, Discovery, MapBasic – GIS;
5. Vertical Mapper – spatial modelling;
6. Encom Discover – spatial modelling for mining environment;
7. AutoCAD Civil 3D – planning;
8. FLAC – rock massive modelling;
9. PLAXIS – geotechnical spatial modelling;
10. Specific mining software (parameters of pillars, productivity, mining equipment cooperation and fleet calculations, Caterpillar and Mining Department of TUT).

Purpose

The main purpose of the research is elaboration of a productive system of digital modelling of mining problems and development plans related to minerals' industry, to analyse usage of BAT and criteria for selecting, planning and design of technological planning.

The research had to prove, by application of digital maps, the possibilities of using BAT at mining of Estonian and other similar resources to decrease the impact of mining on the environment and therefore also the opposition of the society to the use of minerals for Estonian economy.

Particular attention was paid to selection of criteria and basis for BAT, aiming at a decrease in losses of minerals and the impact on the environment in the case of underground oil shale mining. The future purpose is to restrict mining regions by finding out the optimum criteria for resource usage and evaluation of mining impact. The general purpose of the research is optimisation of the usage of mineral resources in Estonia, sustainable development of mining, land usage, resource and subsurface usage.

Hypothesis

Environmental restrictions can be taken into account in digital mining modelling. The general mining modelling software can be improved with options for shallow flat-laying deposits. The created methodology can be used elsewhere where mining conditions are similar, and it offers the possibility to extract minerals in populated areas using a suitable technology with adequate cost.

The expected results of digital planning performed in the study are: effective usage of information, increase in database functionality, new outcomes (designs, theme maps, queries, restrictions), long-term scenarios of oil shale and limestone mining, technological solutions of mining with respect to environmental and social needs. Elaboration of the method of creating sustainable mining conditions and environment is a basic research with practical application for sustainable mining.

The currently existing mining modelling software is not applied in Estonia. Our experience enables to develop and implement it. Mining Department of TUT owns a good but not absolute database for Estonian mining technology and geotechnics [4, 5]. The research creates a new level for solving environmental problems in shallow, flat-laying mineral deposits. Evaluation of mineral resources will be performed in a multifaceted technical-ecological way.

Case 1. Modelling of distribution of mining technology

For modelling environmental impact, data on location and advancing speed of mining are required. Depending on mining conditions, a possible technology, availability of equipment and its productivity, as well as mining areas are chosen. Possible mining technologies in certain mining conditions are the main criteria for restricting a deposit. The main criterion is thickness of the overburden (Table 1) [7].

Since the advancing speed of mining front depends on mining technology and its geometric parameters, the technology has to be modelled for expected geometric parameters. Geometric models with GIS allow to establish suitable mining technologies easily in every certain location. Strip and room-and-pillar mining were modelled with Excel software Visual Basic. In addition Surpac, Encom Discover and Modflow software were used for local cases.

As shown in Table 1, more expensive mining technologies or those not practiced in Estonian oil shale deposit greatly increase the surface mining area and different mining impacts according to water regime and landscape. Open-cast mining with draglines and conveyor bridges and combined stripping methods with excavators and bulldozers allow to increase mineable overburden thickness and to move mines southwards (Fig. 1).

Table 1. **Criteria for mining technology. Respective areas are shown in Fig. 1**

No.	Technology	H_{min}, m	H_{max}, m
1	Traditional surface mining	0	30
2	Opencast mining with draglines	10	27
3	Opencast mining with draglines with re-excavating	23	27
4	Opencast mining with draglines with re-excavating and/or bulldozing	25	33
5	Opencast mining with draglines with re-excavating and/or bulldozing plus excavator-truck stripping	25	35
6	Opencast mining with draglines and conveyor bridges or longwall mining with shearers	30	60
7	Excavator-truck stripping	0	30

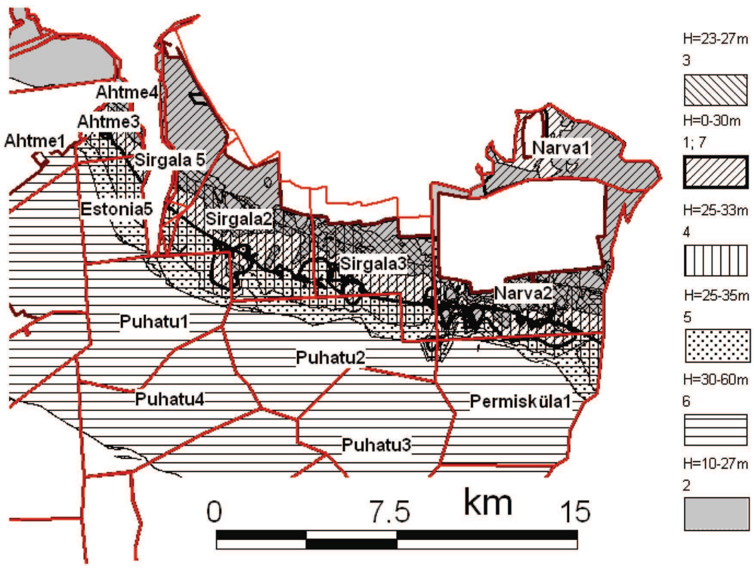

Fig. 1. Possible technologies in mining fields depending on the given criteria. Raster shows technologies according to Table 1.

Case 2. Spatial modelling

Since there was a great amount of drill hole and survey data available, GIS and mining modelling systems were used to solve the spatial task. Spatial distribution and geographical data were retrieved with Vertical Mapper package. For further visualisation of geological data and mined areas, GEMCOM Surpac Vision and Minex were used (Fig. 2).

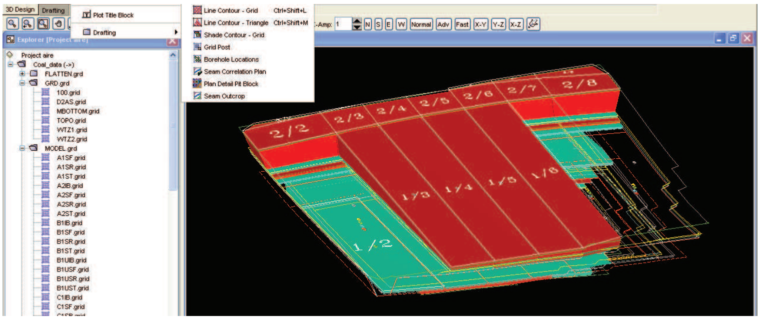

Fig. 2. Modelling software allows to model stripping productivity and sequences.

According to the Estonian law it is allowed to build on the state land which contains mineral resources only if the principles of resource protection are followed and different aspects of the chosen location will not harm possible buildings in any way. Territories with mineral resources or underground mines have to be co-ordinated with planning law at the beginning of the general or detail planning design phase.

The development plan was chosen after analysing all potential technologies, risks and expenses. The plan allows evaluation of environmental and social impacts of mining until the year 2025 (Fig. 3) [7].

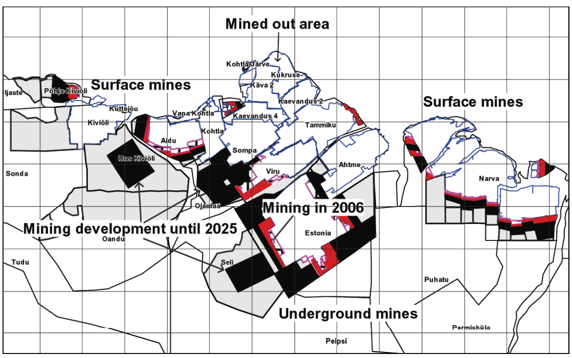

Fig. 3. Development plan of Estonian oil shale mining areas, grid 5×5 km.

Case 3. Mine visualization

Mine planning starts with creating a digital model. The purpose of the model is to show how the landscape will change after mining. The model contains different parts such as: water regime, deposit layout, near-by objects and other elements which are considered to be important to show in the model to reflect the real situation. The model may be created using one or several software programs. In the last case the different parts are divided between software, the outcome being one whole model. The modelling work can be done in parts using one software for mine planning and another one for the reuse of the landscape [2].

Generally all the possibilities are not used in planning, and therefore the modelling will be still done on the two-dimensional scale, which will not give a good overview about the mines to a wide public and therefore may cause some misunderstanding.

After modelling of the initial situation, modifying of the model will proceed according to the mine works. That enables to show the land before, during and after mining. This will be done in pre-planning phase before detailed planning, before starting mine work. The model provides information that enables to find different engineering solutions and the best available one in the current situation.

The model (Fig. 4) can be viewed from different angles playing with different parameters. It is a good visual support when the new mine project is introduced to the general public.

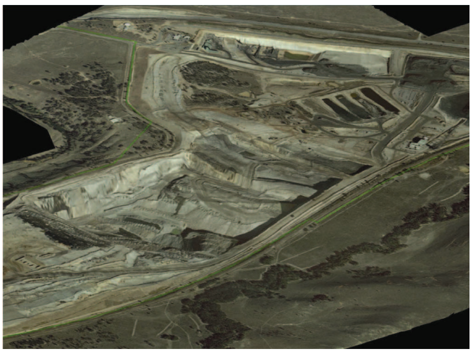

Fig. 4. Example of surface mine visualisation model.

Case 4. Geotechnical problems in sewage project

One problem to be solved in the Jõhvi-Ahtme sewage project was pipeline installation in the mined-out area. Mining Department of TUT evaluated and analysed various possibilities of different pipeline locations taking into account the used mining methods and exact locations of underground workings. The final decision was made by considering Tammiku underground map, surface situation and area boundaries (Fig. 5).

The new sewage pipe is located near the underground mine which geotechnically influences the surface.

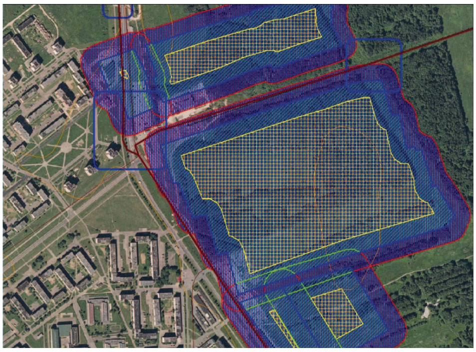

Fig. 5. Sewage area.

Another problem is changing water level in closed mines. The development plan of *Estonian Oil Shale Company Ltd*. is planning opening of a new strip mine in the Tammiku-Kose field. Drainage of the new surface mine affects the existing water regime and that, in turn, may influence stability of underground pillars.

That was the most important reason to avoid location of a pipeline in the area where the room-and-pillar method was used. Because of the karst zone, there are some unmined areas there which were suitable for pipeline location.

Relatively important was the fact that overburden in the mined-out area decreases from 20 meters to 7–10 meters. Six different model versions were under consideration.

It is strongly recommended to investigate and plan before starting to build. The boundaries of mined-out area, land stability and subsidence must be carefully studied. A computer program was worked out to describe the impact [6]. The program presents the basis for future expert estimations.

Discussion

Digital planning of mining fields allows to consider significantly more options and to prognosticate the usage of mineral resources more effectively than the current simple and subjective decision-making process does. Regulating criteria and methodology allows to decrease the costs (time, money, human resource, mineral resource) as well as helps to make decisions concerning the mining process. The experience gained in Estonia will give examples and offer a theoretical basis for utilisation of non-traditional fuels elsewhere. The modelling process allows to optimize the cycle of oil shale mining and explains all stages of designing to the specialists and to the public [2].

Designing the developmental plans for excavating mineral resources (oil shale and mineral resources) has brought up problems at the level of state and local governments. For example, at planning the usage of natural resources – mineral resources, water, land and forest – there are no methods, criteria, equipment or skills that satisfy all the parties.

In addition to the problems of development plans of excavating mineral resources, it gets more and more difficult to find construction fields on the underground-mined area of the Estonian oil shale deposit.

There is enough research on the geotechnical side of the problem, published in [3]. The developed method and a computer program describe the range of influence of the underground-mined area and help to find suitable construction fields on the mined area [6].

To achieve better planning results that would meet the needs of all the parties, it is reasonable to use special geological mining software, because the experience shows that the use of traditional theories and methods will not give detailed results. It is economically more useful to forecast dangerous situations through models than to deal with the consequences later on. Realization of the plans for mined areas with the help of mining software helps to evaluate dangerous situations during engineering already and to eliminate the faults. In addition, it is possible to get information about environmental impact and to make adequate political and strategical decisions.

Conclusions

The results of the research are important for institutions who are working with earth crust. The research raises mining science onto a higher level – digital planning of stratified deposits, based on the long-term Estonian experience, tests and digital planning.

The results will be used for composing country's development plans, in mining planning and in teaching and scientific work.

The work offers better understanding and arguments for public discussion and for mining industry to develop Estonian economy.

During the recent years the research on sustainable mining and creating corresponding indicators has become an urgent issue. Networks such as MMSD (Mining Minerals and Sustainable Development) and SDIMI (Sustainable Development Indicators for the Minerals Industry) stress the importance of working out conceptions based on local professional research. At the same time development of modelling systems for mining and the environment has only begun. The present research enables Estonia to be in the forefront as for modelling and utilising non-traditional fuels.

Department of Mining of TUT has started development research whose various aspects can offer solutions for projects in teaching, science and development. Mining software is applicable in both student exercises for solving different problems and complex use of software – as inputs and outputs for different software types.

Assuming that development research will be useful first of all to the Estonian mining industry and mine companies, it is possible to give recommendations for all Estonian mine planning companies to use one certain software solution and direction and to create criteria necessary for mine studies and for deposit research.

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PAPER II **Karu, V.** (2012). Dependence of land stability on applied mining technology. 11th International Symposium "Topical Problems in the Field of Electrical and Power Engineering", Doctoral School of Energy and Geotechnology, Pärnu, Estonia, 16-21.01.2012, p. 252-255.

Dependence of Land Stability on Applied Mining Technology

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Abstract – **Oil shale is obtained in Estonia with open cast or underground mining. In case of open cast method the area stabilizes within a few years and a new forest is planted on the site. The result of underground mining is undermined land. There are different types of undermined land: steady land, stable land, quasistable land, and subsided land. There exists a number of methods for undermined land evaluation. The first condition for choosing an evaluation method is the information about time, location and method of mining. When the condition is fulfilled, one has to select a suitable evaluation method for a concrete study area. Considering the aforementioned, Department of Mining in Tallinn University of Technology has developed a method and a computer program to evaluate the undermined land areas and to describe the mining impact area. The method and program enable to evaluate the state of undermined land and the risks as well as to plan land utilization and construction works.**

I. Introduction

The principal mining regions of Estonia are: Lääne-Harju (Vasalemma, Padise, Harku, etc. deposits), Ida-Harju (Lasnamäe, Väo, Maardu, etc. deposits), Kunda-Rakvere (Toolse, Ubja, Aru, etc. deposits) and Ida-Viru (Estonian oil shale deposit, peat deposit of Puhatu and many locations for mining building material). The greatest number of problems is faced in old mining regions, while the region is being developed according to the "State plan for utilization of oil shale, 2008-2015", as it is difficult to predict the behaviour of the land in the construction areas utilized according to the plan. On the other hand, the plan contains a design for the development of sustainable mining environment in these regions. Mining environment is understood as the entity of resources (deposits and groundwater), land (agricultural and housing land), engineering, and technology.

In order to ensure the stability and safety of constructions, the results of investigations for detailed planning must provide the input for the designation of primary risk factors and for efficient and economical realisation of planned construction works (building and civil engineering works) [1].

In Estonia oil shale is obtained with open cast or underground mining. When the oil shale area is excavated with open cast method, it stabilizes within a few years and a new forest is planted on the site. Undermined land and surrounding land can be described in following ways: steady land, stable land, quasistable land, and subsided land [7].

Steady land is located on mining claims but is unmined because of protective or remnant pillars. The area of the steady land is always smaller than the area of the pillar.

Stable land is located in pillar-protected areas. Stable land covers the rooms which pillars were not mined before abandoning and where the thickness of the hard roof remains in the range of 10...35 m. Secondary subsidences may occur in the areas with thinner limestone cover.

Quasistable land and area emerges in places where pillars were solid during mining but may break afterwards. All the unstable room-and-pillar mining area is quasistable. Quasistable areas also occur near the sides of mined longwall mining areas, above drifts, adits, and rooms in low-depth mining area.

Subsided land is located above the hand-mined area where advancing and retreating mining and longwall mining with double-unit-face areas were used. The relief of subsided land depends on the roof structure as well as the quantity and quality of the filling material.

Underground mined areas are complex and it is difficult to predict their stability – a problem faced not only in Estonia, but in the whole world [5]. Stability of underground mined areas depends on many factors (extraction time, technology, the thickness of oil shale and many others), some of which are known and some of which are very difficult to identify or even remain unknown [5].

Determination of land stability conditions in Estonian underground mined areas for road construction or other building purposes is quite complicated as different segments of the area were mined at different times, using different mining methods. The difficulty of determining land stability is connected with various parameters of multiple mining methods (e.g. thickness of the seam, type of support etc.) applied in the area.

The problem of land stability has been studied at various sites. The studies are important because a large part of Ida-Viru county is undermined, and developers need the information about the sites and conditions of construction. The main questions of the studies are: How much does the earth sink in the mined areas? How much space remains in oil shale seams? How can describe the undermined land stability?

II. Methods

There exists a number of methods for undermined land evaluation. The first condition for choosing an evaluation method is the information about time, location and method of mining. When the condition is fulfilled, one has to choose a suitable evaluation method for a concrete study area.

Such information can be obtained from old mining plans. To describe the situation in undermined areas, maps of old mining operations have been digitised (with scale 1:10000 and 1:5000), also showing the used mining method (TABLE III).

A. *Digitalisation of Old Mining Plans*

The old mine plans have been drawn by surveyors on paper with application of the local coordinate system. Firstly, it is necessary to establish the plan of what mine it is and its xy coordinates, which will enable to georeference the plan in the map software. The old plans have been scanned and changed into digital files (image files) and opened in map processing software (such as MapInfo Professional). Knowing the coordinates of the scanned map, then digital map is created (Fig. 1.). These plans (with scale 1:10000 and 1:5000) do not give accurate results. The research group has found out that to obtain better results the old mining plans have to be digitalized with scale of 1:2000. The old plans with the scale of 1:1000 and 1:500 would yield even better results but unfortunately many of them have not been preserved. Scanned mining plans enable to identify the location, time and method of mining (see Fig. 1.) as well as the extension of steady, stable, quasistable, and subsided land in the area (Fig. 2.,Fig. 3.).

Fig. 1. Scanned mining plans, digitized mining plan and ortophoto.

B. *The Calculation Method of the Mining Impact Areas*

Department of Mining has developed methods and computer programs to assess and describe the undermined areas and their risks for planned land use and building activities [3]. To draw the mining impact areas, it is first necessary to create a regular grid of thickness or absolute altitude of different soils (see Table). The program uses the algorithm to calculate the mining impact areas (steady, stable, quasistable, and subsided land) [1],[3]. When the grid is ready, the values must be inserted in the contour of the undermined area's block.

TABLE I

EXAMPLE OF BOREHOLE DATA FOR MAKING GRIDS

Borehole number	Ground Surface, m	Quaternary thickness, m	Oil shale bed, m
2545	55	2	40,5
6584	52,5	2,1	41,3
4752	54	2,6	40

NB! Values are indicative

TABLE II

ANGLES FOR DESCRIPTION

Angle	Ground cover (Quaternary)	Limestone
Ultimate angle – angle, which is characterized by the greatest extent of effects of underground mining overhanging terrain coatings	50 °	60 °
Sliding angle – angle, which characterizes the extent of coverage for underground mining dangerous overhanging terrain coatings	50 °	70 °
Breakage angle – angle, which is characterized by tearing off coatings under the influence of underground mining	75 °	75 °

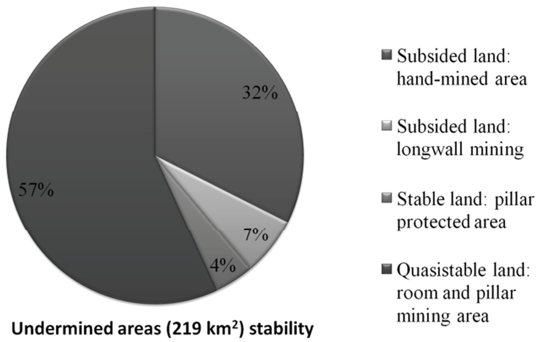


Fig. 2. Undermined areas stability in oil shale deposit.

The impact mining area's extention outside the undermined block's border can be calculated according to the formula:

$$\sum[\, h_i * \tan(90-n_i)], \qquad (1)$$

Where: h_i – layer thickness

n_i – layer ultimate, sliding or breakage angle

The described method provides a basis for further expert assessment including extraction time, movement of the faces, applied technology and equipment. The drawing method of mining impact areas (steady, stable, quasistable, and subsided land) is shown in Fig. 3.

The image of the drawn mining impact areas can be changed, e.g., the areas can be marked with different colours for better understanding. It is not recommended to build anything on quasistable land as it has not yet fully sunk.

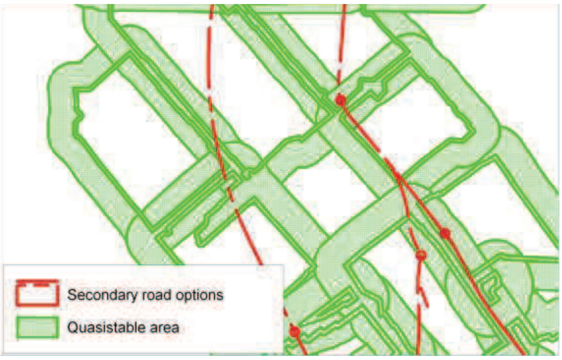


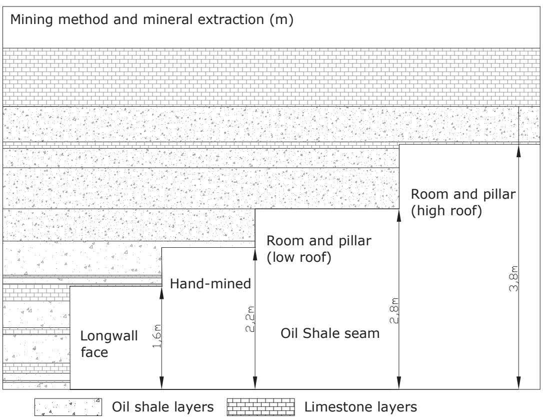
Fig. 3. Drawing method of impact areas.

III. Results

During the ninety years different mining technologies have been used in the oil shale deposit. The price of the extracted oil shale depends on the applied mining technology (see TABLE III). The evaluation method and results of land stability assessment also depend on the mining technology. The calculation method described above is employed to calculate the stability areas (steady, stable, quasistable, subsided).

TABLE III

Used Mining Methods and Working Height in Oil Shale Seam



Using the results of the calculation method, it can be said that the undermined area in Kukruse-Tammiku secondary road region is mostly quasistable – it means the limestone layer and elements of the support were not broken during the extraction, but it may happen later [2].

The possible maximum land subsidence is different and depends on the applied mining method. Land subsidence ranges 0,90…1,84m (see TABLE IV) and causes cracking of rock, which in its turn generates additional empty spaces, depending on the thickness of the overburden and mined oil shale seam (see TABLE V).

The following are the study results of the Mine no 4 area. Using the aerial photograph and the altitude data (known as LIDAR data) it has been found out that the longwall areas have sunk. On the basis of the analysis of longwall subsidence it can be said that the subsidence of the land is 0.50 ... 0.70 m. Such subsidence encourages the formation of wetlands, and water filled old mine shafts as the area had originally been quite marshy (Fig. 4).

TABLE IV

Maximum Land Subsidence Depending on Mining Technology

Mining technology	Land subsidence, m
Hand-mined	1.32
Room and pillar	1.84
Longwall face	0.90

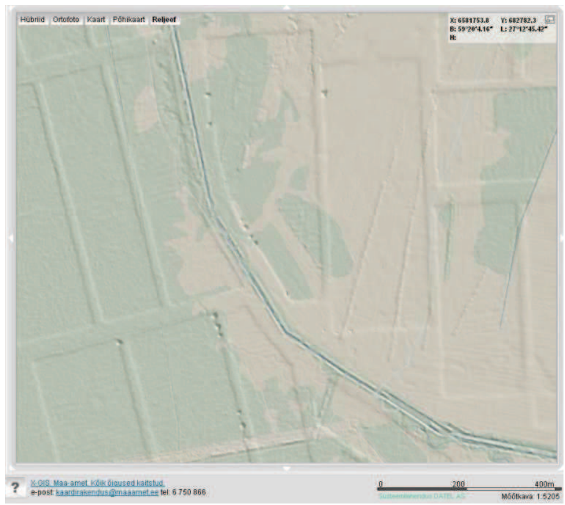


Fig. 4. Subsidences in undermined area.

IV. Discussion

The undermined areas can be easily mapped with the help of the devised method and programs. Studies have shown that oil shale room and pillar mining area is stable if mining depth was less than 35...40 meters. In the old mining fields with drifts in the mines the friable overburden may collapse, where its thickness is less than 10...12 meters. Quasistable land initially behaves like the stable, but various types of dangerous earth movements occur later and the collapse causes the appearance of holes in the area's land.

Undermined land's quasistability is one of the major problems caused by mining, which is difficult to assess. A more extensive use of mining plans with the scale of 1:1000 and 1:500, application of LIDAR and 3D scan data enables a more exact evaluation of the undermined areas and a better understanding of rock and sediment layers' behaviour as well as the stress areas linked to it.

TABLE V

MINED AREA

Options	Kukruse	Mine no 2	Käva	Käva 2	Mine no 4	Tammiku	Sompa	Kohtla	Ahtme	Viru	Estonia
Mine opening	1921	1949	1924	1924	1953	1951	1948	1937	1948	1964	1972
Mine closing	1967	1973	1972	1972	1975	1999	1999	2001	2001		
Working time, year	46	24	48	48	22	48	51	64	53		
Field area, km^2	13.20	12.30	3.47	14.05	12.70	40.00	33.60	18.30	43.30	41.70	141.10
Mined field area, km^2	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36	25.49	62.77
Not mined area, km^2	-1.93	3.73	1.63	2.33	2.27	20.74	15.46	6.16	16.94	16.21	78.33
Thickness of overburden, m	11	13	21	10	12	23	23	15	37	42	57
Thickness of oil shale seam, m	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79	2.75	2.71
Geological space in oil shale seam, mln m^3	**42.82**	**24.08**	**5.22**	**33.05**	**29.20**	**53.92**	**50.24**	**33.52**	**73.53**	**70.09**	**170.11**
Mined oil shale seam thickness, m											
Hand-mined face	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Hand- mined rooms	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Room and pillar	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79	2.75	2.71
Drifts	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79	2.75	2.71
Longwall face	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Mined field area, km^2											
Hand-mined face	11.28	6.87		9.16	7.71	4.36	12.70	3.80	6.33	0	0
Hand- mined rooms	3.50	0.00	1.84	1.73	0	0	0.06	1.36	0.05	0	0
Room and pillar	0.29	1.70		0.79	1.08	11.81	1.86	0.55	19.22	25.38	61.49
Drifts	0.06	0.00	0.00	0.04	0.69	0.36	0.00	0.02	0.30	0.11	1.26
Longwall face	0	0		0	0.95	2.74	3.52	6.41	0.46	0	0.02
Total mined area	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36	25.49	62.77

V. CONCLUSIONS

The main questions of the studies were: How much does the earth sink in the mined areas? How much space remains in oil shale seams? How can describe the undermined land stability? Scientists have a set of methods to predict the subsidence and to evaluate its parameters, though it is difficult to forecast the exact time of its occurrence. There are also measures to prevent and mitigate flooding. To get better results the collapsing areas at undermined sites should be assessed. Specifying the collapse locations, their mining methods, geological conditions and other parameters can enable a better evaluation of the extend of the collapse influence area. The aforementioned data will enable construction specialists to assess the safety conditions of the roads to be built and expenditures linked to it.

ACKNOWLEDGMENTS

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PAPER III Erg, K.; **Karu, V.**; Lind, H.; Torn, H. (2007). Mine pool water and energy production. 4th International Symposium "Topical problems of education in the field of electrical and power engineering" Doctoral School of Energy and Geotechnology, Kuressaare, 15-20.01.2007. (Ed.) Lahtmets, R. Tallinn University of Technology Faculty of Power Engineering, p. 108-111.

Mine pool water and energy production

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Abstract

Mine pool water and energy production issues intersect in numerous ways. However, water and energy are often not in the proper balance. For example, even if water is available in sufficient quantities, it may not have the physical and chemical characteristics suitable for energy or other uses. Pre-mining time groundwater goes through geochemical processes when formed natural with low sulphate content groundwater. The oil shale mines dewatering lowered groundwater level in Keila-Kukruse layer, and the sulphate content increasing about 50 times by intensive oxidation of pyrite.

The use of mine pool water is technically feasible and can be approved under existing regulatory authorities. Nevertheless, mine pool water is not widely used today.

Keywords

Closed mining sites, mine pool water, energy, dewatering, sulphate content, oil shale, Ida-Viru County.

Introduction

Nearly every European country has closed mining sites [1, 2, 3, 4]. Closed underground mines may induce risks for the environment. Some of these risks are linked to the shut down of the mine water pumping operations leading to a water level rising and the pollution of groundwater by sulphates and others chemical elements. After the mine closing these risks may exist during a short, long and very long period of time depending on the quantity and flow of water involved and the volume of the mine workings concerned [5]. Generally, the water of closed mines in oil shale area meets the requirements of the Drinking Water Standard of Estonia (RTL 2001/100/1369). Environmental benefits can result in connection with the use of mine pool water at some locations. Throughout the oil shale region of Ida-Virumaa, numerous mines are currently discharging to streams and rivers. Water from flooded underground mines represents a large untapped resource for power plant cooling. These mines water “reservoirs” could serve as a source of water to replace surface water sources.

Description of Study Area

The closed oil shale mines are located in central part of oil shale deposit (Fig. 1) and the area is about 176 km^2 (Table 2). From a hydrogeologic standpoint, the oil shale deposit is divided into three principal hydrostratigraphic units associated with a northeast and east topographically driven flow with recharge zones at the highest outcrops and discharge zones in the rivers. Oil shale mining affected the groundwater regime and chemistry of Quaternary and Ordovician aquifer. Hydraulic properties of the aquifers are summarised in Table 1.

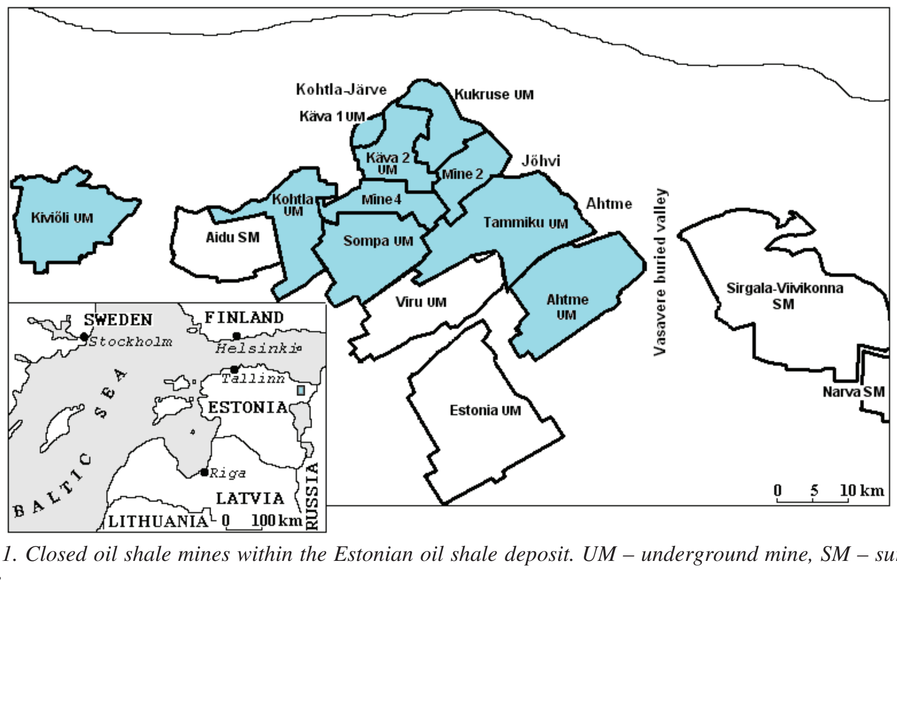

Fig. 1. Closed oil shale mines within the Estonian oil shale deposit. UM – underground mine, SM – surface mine

Table 1*. The hydraulic properties of aquifers in the Estonian oil shale deposit [6].*

Age	Aquifer system	Rock type	Depth, m	Thick-ness, m	Water table (piezo-metric), m below surface	Specific capacity, l/sec/m drawdown	Hyd-raulic conduc-tivity, m/day	Trans-missi-vity, m^2/day
Quaternary	Q	Sand, till, peat	0	0-77	+0.3-16	0.001-54	0.02-175	0.1-1980
Ordovician	Nabala-Rakvere O_2nb-rk	Lime-stone, marl, dolostone	2-20	0-50	+0.1-13.2	0.025-11.0	0.40-185	4-2546
	Keila-Kukruse O_2kl-kk		0.5-50	0-44	0.2-28.2	0.007-8.3	0.04-170	0.03-2308
	Lasnamäe-Kunda O_2ls-kn		0.5-100	17-24	0.6-15.6	0.001-2.1	0-48	0.01-187

Quaternary deposits comprise a thin layer of peat, sand and till and unconsolidated glacial sediments that constitute porous aquifers with mainly unconfined groundwater [6], influenced directly by the meteorological conditions. The surface water percolates directly into the Quaternary cover, and most of the groundwater flows through the cover as the groundwater discharges into springs, streams, rivers and wetlands.

Ordovician aquifer system consisting of lime- and dolostones with clayey interlayer lenses are found below the shallow cover of the Quaternary deposits in oil shale deposit. The limestone may be divided into a near-surface karst aquifer, cutting across the stratigraphic units, and several deep fracture aquifers, corresponding to the stratigraphic units [6, 7, 8]. The lateral near surface hydraulic conductivity of the Ordovician limestone is in the range of 5–300 m/d, whereas it is only 0.1 m/d [9] at a depth of 80–100 m. The vertical conductivity of the clayey layers separating the water-bearing zones is 10^{-5} – 10^{-2} m/d [9]. Therefore, these clayey layers serve as aquitards, dividing the limestone in many local aquifers of different vertical and horizontal extent. Long-term observation results [9] show that the inflow to the mines varies with the seasons. Of the total water amount 20% falls to the winter months, 29% to the spring months, 27% to the summer months and 24% to the autumn months. Rainfall is characterized by an inter-annual irregularity. The weather impact on the mine decreases with the depth of the mine and the coefficient of inflow irregularity decrease by 2.3% while mine become deeper 1%.

Mine Pool Development

Extensive pumping was needed to keep the mines free from water. When the mines became inactive, groundwater flooded the mines. Water levels in the mine would continue to rise until hydraulic equilibrium with the regional water table was achieved or the water followed paths to topographically low areas. Fractures caused by roof cave-ins, removed or breached pillar barriers as well as tunnels and shafts, allowed water to freely flow within one mine or a series of mines (commonly referred to as mine complexes).

After pumping of water stops the old shafts and tunnels fill up with water. In underground oil shale mines, there may be a number of disconnected pools at the early stage of flooding. Before flooding water sub-pools may exist at various locations and elevations within the mine. The abundance of sub-pools is greatest at the back of the mine where recharge and leakage collect. These sub-pools tend to coalesce and form a main pool, which will rise from the back of the mine in an up-dip direction. As flooding progresses, the sub-pools join into a single main pool with big water volume (Table 2). The flooding situation is a transient scenario, while the flooded case is a steady state one. In transient groundwater flow systems, hydraulic head is continuously changing with time, with minor seasonal or annual fluctuations. In 2004, the volume of water in the pools of the closed underground mines was about 165 million m^3; in 2004 it amounted to 138 million m^3 (Table 2).

Table 2. Approximate water volume in closed underground oil shale mines

Underground mine	Work started	Closed (pumping stopped)	Water table in 2003, [14]		Mined out area, km^2 [14]	Water volume (approximately), 10^6 m^3	
			Obs.well no.	m, a.s.l.		2004	2006
Kukruse	1916	1967	8214A	52	13	5	3
Käva	1924	1973	2	51.5	18	10	8
Kohtla	1937	28.06.2001	W-15	41	17	13	9
Ahtme	1948	1.04.2002	16122	25	35	63	50
Sompa	1949	2.12.2000	487	43	27	23	22
Mine 2	1949	1974	3a	51.41	13	7	6
Tammiku	1951	28.12.1999	714 8208 1099	47.95 50.04 47.92	40	42	38
Mine 4	1953	1975	302 1b	41.18 40.26	13	2.0	1.5

The elevation of the water table in 1990 was about 42–53 m above sea level (Fig. 2 A) in Käva and Kukruse mines, Mine no 2 and Mine no 4. In some cases, water levels in two or more adjacent mines will fluctuate in conformity with the seasonal or man-induced stresses. Hydrologic investigations indicate that the elevation of the water table has fluctuated over time, especially in Mine no 2. The maximum elevation was about 51 m a.s.l., but seasonally it fluctuated between 50–56 m a.s.l., primarily as a result of variation in climate and increased precipitation. If the inflow rate is all the time greater than the outflow rate, the water storage and hydraulic head in the saturated portion of the mine will increase. If outflows are greater than inflows, then the hydraulic head will decline.

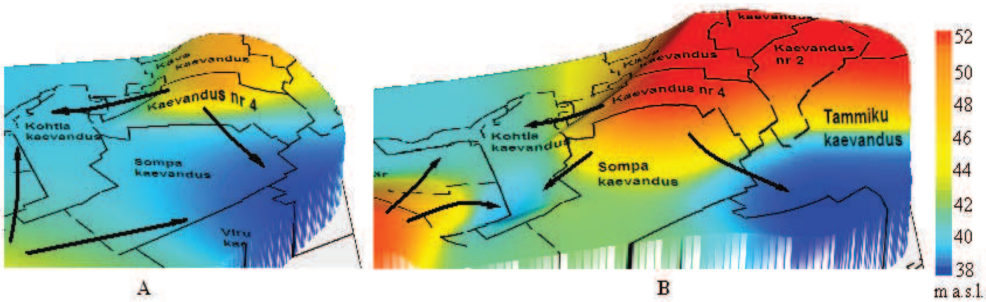

Fig. 2. Water level in the Keila–Kukruse groundwater aquifer in 1990 (A) and in 2003 (B).

During the rainy August of 2003, the water table rose 4 m in Sompa underground mine, 2 m in Kohtla, 2.1 m in Kukruse, 1.8 m in Mine no 4 and 0.5 m in Ahtme mine. Closed mines water filling and restoration of Keila-Kukruse underground water level in 2003 is presented in figure 2 B.

The dissolution of pyrite leads to high concentrations of sulphates. The water displayed neutral pH and positive Eh in the spring-summer than in other times. These results reflect the increasing of the sulphide oxidation rate during the warm months, other time the sulphide oxidation rate was low, but depend on precipitation. In recent years, in the area of oil shale mines, the chemical composition of groundwater has been stable. The content of SO_4 in groundwater was 2 times higher in spring than during the remaining seasons of the year. The sulphate content in the water filling up mine is high; in the closed mines it is low (Fig. 3).

However, mines may not generate sufficient water. Discharge from underground oil shale mine individually to sustain a consumptive use as large as a power plant.

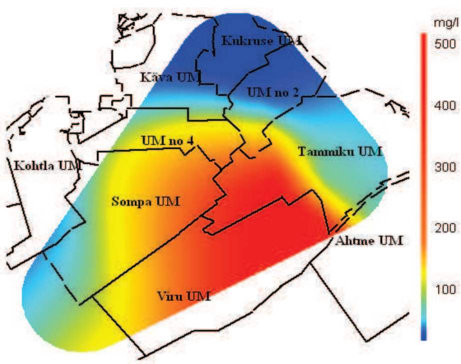

Fig. 3. The sulphate content in the Ordovician Keila–Kukruse aquifer of underground oil shale mine area.

In fact, large power plants can evaporate thousands of cubic meters per minute in order to maintain their operations. Therefore, a number of mines may have to be linked hydraulically, either by direct connection or through the use of mine to mine transfer pumps to obtain an adequate cooling water supply.

Conclusion

Mine pool water may use at some small facilities. Because other, more traditional fresh water sources have been available historically, there has been little incentive to explore new water supplies. Before the resource can be more fully utilized, many questions will need to be answered, and industrial users, regulators, and the public must gain a better understanding of the value and potential impacts of using mine pool water.

Some of the areas that require further investigation include:

1. better characterization of the locations and volumes of mine pools;
2. better characterization of the variation in water quality parameters at various mine pools;
3. hydrological information relating to recharge rates;
4. the potential for ground surface subsidence as water is removed from mine pools.

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PAPER IV Valgma, I.; Tammeoja, T.; Anepaio, A.; **Karu, V.**; Västrik, A. (2008). Underground mining challenges for Estonian oil shale deposit. Schacht, Strecke und Tunnel, TU Bergakademie. Buhrow, Chr.; Zuchowski, J.; Haack, A. (Ed.). Freiberg, p. 161-172.

Underground mining challenges for Estonian oil shale deposit

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Overview of oil shale in Estonian power industry

Estonian power industry is characterized by great share of oil shale - oil shale is the main energy source for power generation and has its part in heat energy. The share of oil shale in power generation in 2005 was over 90 percent. Total share of oil shale in power and heat energy generation was nearly three quarters (Figure 1).

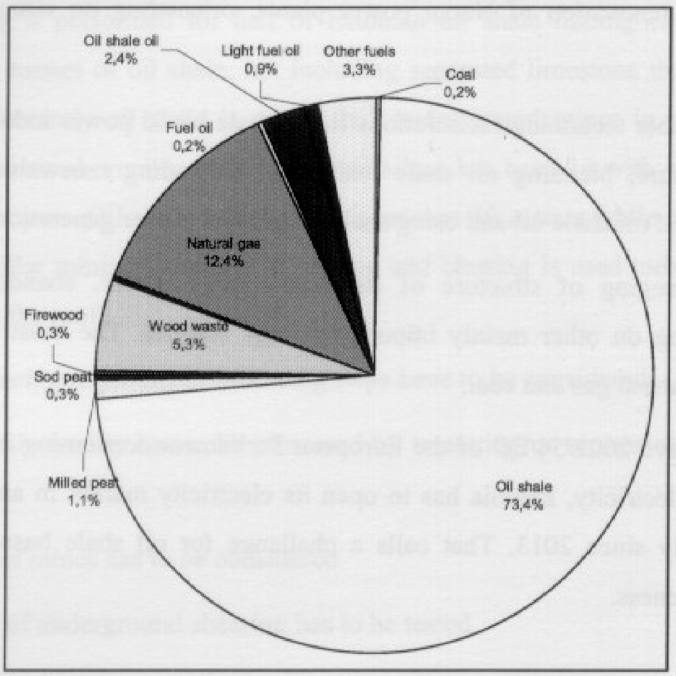

Figure 1: Fuels used for power and heat generation in Estonia in 2005

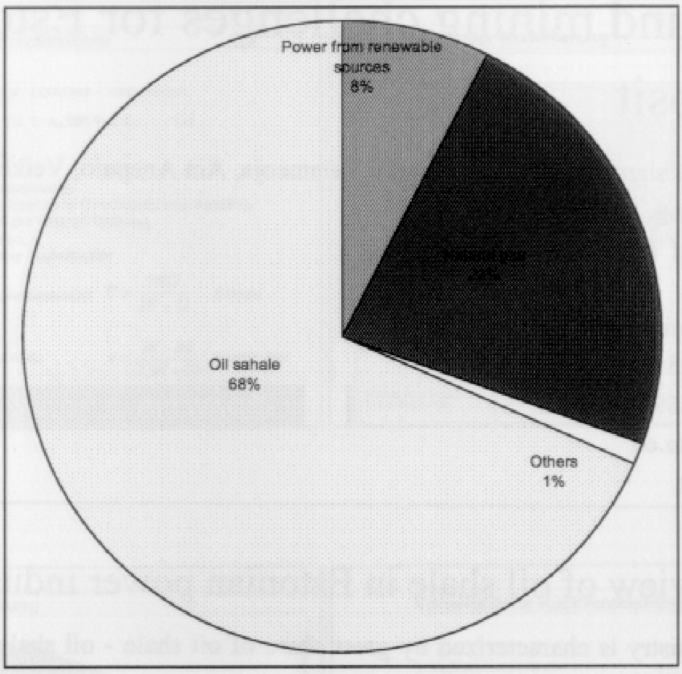

Figure 2: Predicted share of fuels for power generation in 2015

Plans for continuing oil shale industry are characterized by following principles:

1. Continuing renovation of Narva power plants, orientating on circulating fluidized bed technology.

2. Applying other technological solutions in oil shale based power industry like combustion under pressure; blending oil shale with other (including renewable) fuels; large scale production of oil shale oil and using shale oil in local power generation.

3. Radical changing of structure of Estonian energy sector, abandoning oil shale and concentrating on other mainly imported energy sources. The most possible alternatives would be natural gas and coal.

According to Directive 2003/54/EC of the European Parliament concerning common rules for the internal market in electricity, Estonia has to open its electricity market in amount of 35 per cent since 2009 and fully since 2013. That calls a challenge for oil shale based power industry to maintain competitiveness.

Table 1: Oil shale consuming industry in 2007

		Eesti Power Plant	Balti Power Plant	VKG Aidu Oil OÜ	Kiviõli Keemia-tööstuse OÜ
Field of use		electricity/oil	electricity	oil, chemistry	oil, chemistry
Quality agreed in contract **	MJ/kg	8,4	8,4	11,32	11,32
Quality agreed, in upper heating value figures ***		10,70	10,70	13,86	13,86

* Calculated, not official

** Contract states the lower heating value and limit of moisture content

*** calculated in moisture content of 12% for VKG Aidu Oil and Kiviõli Keemiatööstus and in moisture content of 10% for all other consumers

Underground mining is performed for half of Estonian oil shale mining capacity. It is done in amount of 7 million tonnes of oil shale, not including separated limestone that is 40% of mass in addition per year. Currently oil shale is mined in 2 underground mines in addition to 7 surface mining fields. The maximal number of underground mines has been 13 with total annual output of 17 million tonnes per year. Oil shale bedding depth reaches 80 meters while seam thickness is 2,8 meters. Room and pillar mining system with drilling and blasting is used today with square shape pillars left to support the roof.

For solving CO2 reducing requirement following steps have to be considered:

- Trade oil shale quality has to be increased by removing or separating limestone from the material
- Backfilling of mines has to be considered
- Technology of underground shearing has to be tested

For increasing trade oil shale quality, removing or separating limestone from the material has to be performed.

The main option used today is Heavy media separation (HMS). Other, currently being tested, is high-selective mining with surface miner. The main task for mechanical cutting is cutting selectively oil shale (15MPa) and hard limestone (up to 100MPa). The oil shale seam consists up to 50% of limestone layers and pieces. This raises a question of utilising waste rock or ash on the waste material deposit or in surface or underground mine.

Table 2: Production figures of oil shale mines in, 2004/05

	Unit	Estonia mine	Viru mine	Aidu open cast	Narva open cast
Total trade oil shale	106 t	4,71	1,91	1,93	4,73
	MJ/kg, lower	11,250	11,947	11,160	10,694
fuel oil shale	106 t	3,85	1,19	1,72	4,73
	MJ/kg, lower	10,696	10,780	10,816	10,694
concentrated oil shale	106 t	0,86	0,71	0,21	
	MJ/kg, lower	13,835	13,887	13,817	
Run-of-mine	106 t	8,34	3,05	2,65	4,73
Trade oil shale share in ROM	%	56,5%	62,5%	72,7%	100,0%
Waste rock (limestone)	106 t	3,63	1,14	0,72	0
Share of waste rock	%	43,5%	37,5%	28,3%	0,00%
Design production*	106 t	5	2	2	5

* designed production is annual possible amount of trade oil shale according to initial project concerning 60 per cent oil shale and 40 per cent waste.

It is just becoming an issue that oil shale mining and further processing in power plant or oil factory is in same sequence and optimal heating value may differ from current values. Issues are becoming more topical with raising environmental taxes. Higher heating value also results in reduced emissions of CO2 and ash.

Mining conditions

Oil shale bed in Estonia is deposited in the depth of 0…100 m with the thickness of 1,4…3,2 m in the area of 2489 km^2. The mineable seam consists of seven kukersite layers and four to six limestone interlayers. The layers are named as A…F1. The energy rating of the bed is 15…45 GJ/m^2.

The feasibility of the oil shale mining depends on energy rating, calorific value of the layers, thickness and depth of the seam, location, available mining technology, world price of competitive fuel and its transporting cost, oil shale mining and transporting cost. In addition, nature protection areas are limiting factors for mining.

The economic criterion for determining Estonia's kukersite* oil shale reserve for electricity generation is the energy rating of the seam in GJ/m^2. It is calculated as the sum of the products of thickness, calorific values and densities of all oil shale layers A-F1 and limestone interlayers. A reserve is mineable when energy rating of the block is at least 35 GJ/m^2 and sub economic if energy rating is 25…35 GJ/m^2. According to the Balance of Estonian Natural Resources, the oil shale reserve was 5 billion tonnes in the year 2000. Economic reserve was 1,5 billion t and sub economic 3,5 billion t. These figures apply to oil shale usage for electricity generation in power plants. In the case of wide-scale using of oil shale for cement or oil production, the criteria must be changed. Therefore in changing economical conditions it is important to know operating expenditures and possible revenue.

There is a question how much money will mine loose if oil shale sold is of higher calorific value than it is stated in contract. Simplified approach for that is to calculate the per cent difference of heating values and reduce profit by the same percentage. In reality, fixed and variable costs must be taken into account and the fact that in client (power plant in our case) gets more energy from oil shale tonne, the one requires less oil shale and reduces the order by respective amount or even by

* In addition to kukersite oil shale in Estonia, there are occurrences of another kind of oil shale – dictyonema argillite, mined and used in Sillamäe for extracting uranium in 1948…1953.

bigger amount of oil shale due to increased efficiency (Table 3:Example of lost money by selling oil shale of higher quality than in contract).

If a mining enterprise will sell 1 194 thousand tonnes of fuel oil shale with lower heating value of 8,4 GJ/t and 712 thousand tonnes of concentrate, the amount of losing money is presented if average heating value of sold fuel oil shale 8,6 MJ/kg. First column indicates base case.

Table 3: Example of lost money by selling oil shale of higher quality than in contract

	1.	2.	3.	Units
Lower heating value according to contract	8,4	8,6	8,6	GJ/t
Amount of fuel oil shale sold	1 193 704	1 193 704	1 167 359	T
Amount of concentrated oil shale	712 406	712 406	712 406	
Upper calorific value of fuel oil shale	10,702	10,944	10,944	GJ/t
Lower calorific value of fuel oil shale	8,4	8,6	8,6	GJ/t
Moisture content of fuel oil shale	12	12	12	%
Upper calorific value of fuel oil shale	13,887	13,887	13,887	GJ/t
Amount of energy in fuel oil shale	12,8	13,1	12,8	PJ
Amount of energy in concentrated oil shale	9,9	9,9	9,9	PJ
Cost price of trade oil shale	7,55	7,64	7,67	EUR/t
OpEx	14 396	14 568	14 431	Thousand EUR
Increase of OpEx		171	35	Thousand EUR
Less income from sale (7,81 EUR/t)			206	Thousand EUR
Total less income			241	Thousand EUR

The main interested partners for the tests could be Oil Shale Companies in Estonia, Oil producing company, Mining Department of Tallinn University of Technology, Estonia, (http://mi.ttu.ee/mining), Continuous Miner (or road header) producer, partner research group or institute working together with the machinery producer, process equipment (crusher, sizer, screen, gravity separator) producer, pump (pumps, dewatering and backfilling systems) producer, support (supporting, bolting) producer.

Fine separation is needed for enriching fine part of limestone and oil shale mixture. Possible solutions are drying, pneumatic separation, heavy media separation, water jet separation or others.

Crushing

Sizers or other types of crushers are needed for getting oil shale fraction 0-15 mm, and limestone 0-45 mm. Since fines are difficult to handle both in power plant and oil generation process, the share of 0-5mm should be minimum.

Screening

Roll screens or banana screens are required for screening of fines of oil shale material. This avoids double crushing of the sized material. It is possible, that drier should be used together with screening, crushing and storing operations.

Continuous miner

Continuous miners are needed for non-blasting operations in new potential underground oil shale mines. The main requirement is to cut hard limestone and soft oil shale with the same machine.

A longitudinal cutting head type was first introduced in the former Soviet Union by modifying the Hungarian F2 road headers and in 1970s in Estonia by modifying the Russian coal road header 4PP-3. Evaluation of breakability was performed by a method developed by A. A. Skotchinsky Institute of Mining Engineering (St Petersburg, Russia). For this purpose over a hundred samples produced by cutting of oil shale and limestone, as well as taken in mines by mechanical cutting of oil shale were analysed. In researches evaluations were made for using coal-mining equipment for mining oil shale.

Comparative evaluations were made by the experimental cutting of oil shale in both directions – along and across the bedding, including also mining scale experiments with cutting heads rotating round horizontal (transverse heads) and vertical axes (longitudinal heads). In both cases the efficiency was estimated by power requirement for cutting. The feasibility was shown of breaking oil shale by direction of cutting across the bedding by using cutting drums on horizontal axis of rotation. The research also evidenced that the existing coal shearers proved low endurance for mining oil shale. Therefore, the problem arose of developing special types of shearers for mining oil shale or modifying the existing coal shearers.

It was further stated that the better pick penetration of the longitudinal machines allows excavation of a harder strata and at higher rates with lower pick consumption for an equivalent sized transverse machine. It was reported that with the longitudinal cutting heads the dust forming per unit of time decreases due to smaller peripheral speed. The change in the magnitude of the resultant boom force reaction during a transition from arcing to lifting is relatively high for the transverse heads, depending on cutting head design. Specific energy for cutting across the bedding with longitudinal heads is 1.3–1.35 times lower which practically corresponds to the change of the factor of stratification.

The results of these tests were used in large body of fundamental research into rock and coal cutting in the (United Kingdom) UK during the 1970's and early 1980's at the UK Mining Research and Development Establishment.

Three decades ago a progressive mining method with continuous miner, which is most suitable for the case of high-strength limestone layers in oil-shale bed, did not exist in oil-shale mines of the former USSR and in Estonia. Therefore, up to now oil shale mining with blasting is used as a basic mining method in Estonia minefields while continuous miner was tested for roadway driving only. With regard to cutting, the installed power of coal shearers and continuous miners has increased enormously since the original work. Actual state of the market has changed and a wide range of powerful mining equipment from well-known manufacturers like DOSCO, EIMCO, EICKHOFF, etc. is available now.

We have 30 years of experience in cutting with longwall shearers which were not capable of cutting hardest limestone layer inside of the seam. Tests with road headers have been carried out in 1970ties.

We have tested Wirtgen surface miner SM2100 and SM2600 for two years and SM2200 and Man Tackraf surface miner, and are currently testing Wirtgen surface miner SM2500 for high selective mining in an open cast mine.

Due to horizontal lying of layers, cutting faces parallel or inclined shearing forces when using rotating cutting heads in the seam (Figure 3:Oil shale cutting principles).

In the case of longwall cutting scheme that was used in Estonian oil shale mines (Sompa, Ahtme, Kohtla, Tammiku) the cutting head situated in the middle of the seam, allowing cutting tools to cut layers perpendicularly. As shown in upper drawing main cutting is performed in "green zone" that requires less energy and consumption of cutting tools is low (upper drawing Figure 3).

The other scheme, currently tested high selective shearing with surface miner works with the same principle, using advantage of cutting in direction of free surface (middle drawing Figure 3).

The third option that is not tested, is working in "red zone" cutting toward parallel shearing force, requiring presumably most energy and the consumption of cutting tools is highest (lower drawing Figure 3).

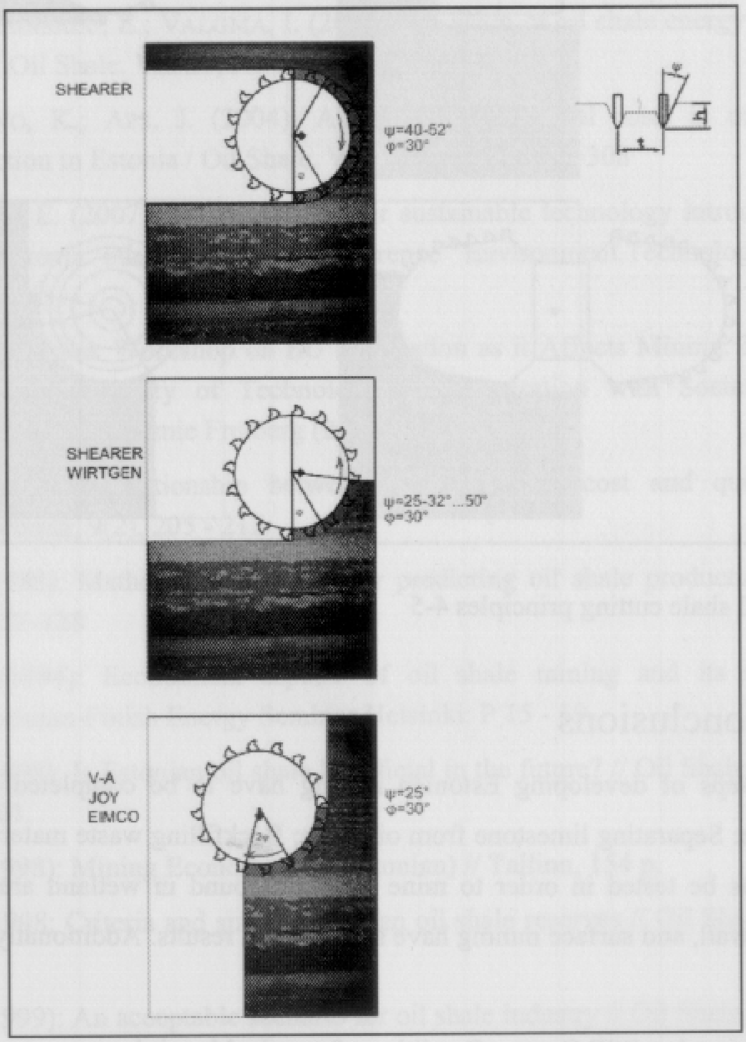

Figure 3: Oil shale cutting principles 1-3

In case of vertical shearing, horizontally placed cutting cylinder is not forcing any parallel shearing opposition and should be most effective way. The problem is that there are no suitable continuous miners on the market at the moment (upper drawing Figure 4:Oil shale cutting principles).

Fifth option is using cylinder with cutting tool that are situated both in top and the perimeter of the cylinder. It meets mainly “red zone” forces (lower drawing Figure 4). In the third option that is not tested, is working in “red zone” cutting toward parallel shearing force, requiring presumably most energy and the consumption of cutting tools is highest (lower drawing Figure 3).

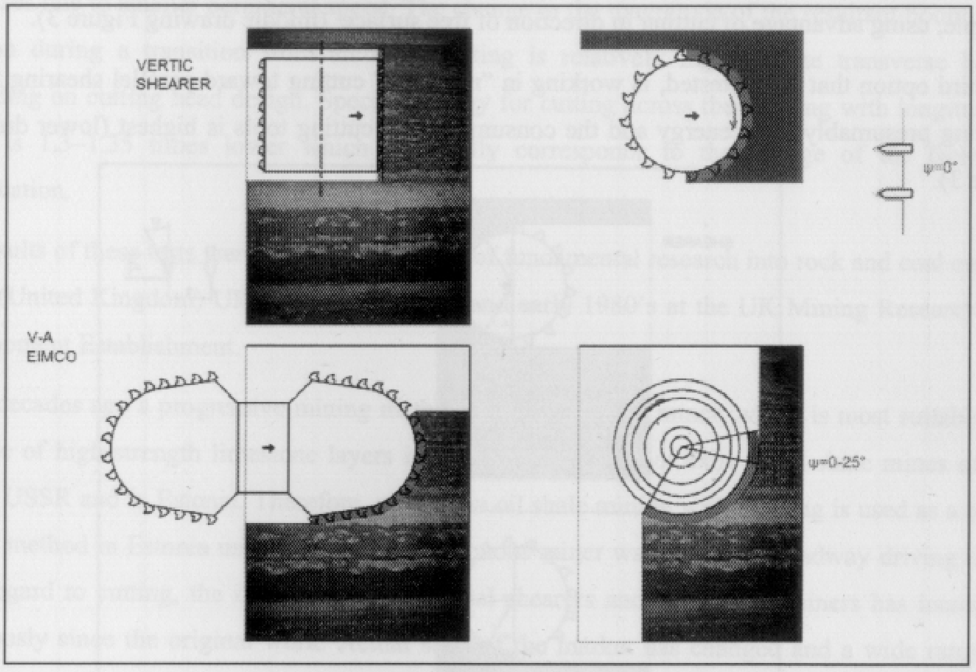

Figure 4: Oil shale cutting principles 4-5

Conclusions

Three main steps of developing Estonian mining have to be completed in order to normalise resource usage: Separating limestone from oil shale; Backfilling waste material into mine and short wall mines has be tested in order to mine in underground in wetland areas. Previous test with shortfall, longwall, and surface mining have shown good results. Additionally fine separation has to be tested.

This study is related to ESF Grant – Condition of sustainable mining.

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Potential of underground minewater in Estonian oil shale mining region

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Abstract

Underground oil shale mining creates underground pools of water called technogenic water bodies. For defining underground space properties, classification of used mining technologies has to be created and evaluated for defining hydrogeological parameters. Classification helps defining space that is available for water in abandoned mines. 3D model was built with geometrical data from mine plans, mine closing acts and borehole data and from land survey data. The main tools chosen for spatial modelling were spreadsheets and MS Access databases for systemising and querying data, Mapinfo for georeferencing, Vertical Mapper for interpolating and grid calculations and Modflow for pumping simulation. With help of interpolated grids, surface elevations, layer thicknesses and required properties were calculated. The main aim of this paper is to find out parameters of water and its media that influence amount and availability of energy in Estonian oil shale underground mining area.

Keywords

Undermined, mines, minewater, energy, hydrogeology

Introduction

Underground oil shale mining creates underground pools of water called technogenic water bodies. At the same time abandoned mining creates infrastructural problems for local people. Industry that has been directly related to mining is leaving the area because of lacking source fuel or source materials. The side product of the industry has been power supply, road maintenance and services. Local authorities have to find alternative energy resources instead of former industry related sources. One of the potential sources of energy could be heat or kinetic energy of minewater. The water that has filled the mines or is pumped out from a mine could be called minewater. The main properties of minewater are storage, volume, temperature, level and quality parameters. Water storage or productivity of potential energy unit is related to the media where water is flowing. In current case the media is underground mine and its covering rocks. The main aim of this paper is to find out parameters of water and its media that influence amount and availability of energy in Estonian oil shale underground mining area.

1. Study area

Underground oil shale mining has been performed for 90 years in the middle-north part of Baltic oil shale basin in Estonian deposit (Figure 1). The depth has been lower in central-northern part, thickness and quality has been greater in the same area. This was the reason why mining started in 1916 moving toward wings of the deposit where mining conditions worsened (Kukruse area, Figure 1).

For calculating potential amount of water the underground space and its properties should be defined. Since underground space forms from mine workings, roof structure and related water channels or tubes, this situation has to be mapped in 3D. For defining underground space properties, classification of used mining technologies has to be created and evaluated for defining hydrogeological parameters. Classification helps defining space that is available for water in abandoned mines. 3D model was built with geometrical data from mine plans, mine closing acts and borehole data and from land survey data.

2. Spatial modelling

The geometrical parameters for the model are oil shale seam bottom height, roof height, length, with and height of pillars and workings in the mines, thickness of overburden that is divided into required number of sublayers by different storativity values.

The main tools chosen for spatial modelling were spreadsheets and MS Access databases for systemising and querying data, Mapinfo for georeferencing, Vertical Mapper for interpolating and grid calculations and Modflow for pumping simulation.

With help of interpolated grids, surface elevations, layer thicknesses and required properties were calculated. Dynamic model must be checked with a spreadsheet as well as the amount of water to find the study area, using the same parameters to be entered in the ModFlow model.

3. Hydrogeological properties and modelling

Since hydrogeological situation has been changed relatively fast due to closing down several mining operations and stopping pumping in these regions, dynamic model has to be created, simulating groundwater level, amount of water in working and abandoned underground mines and potential productivity of wells starting to operate for energy extraction.

For creating a hydrogeological model following parameters related to mining activity have to be decided like properties and parameters of overburden and oil shale seam, porosity, hydraulic conductivity, water quality parameters, groundwater initial head and amount of pumped out water from underground mines. Main hydrogeological characteristics for hydrogeological model are porosity, vertical and horizontal hydraulic conductivity, infiltration rate, storage and information about water aquifers.

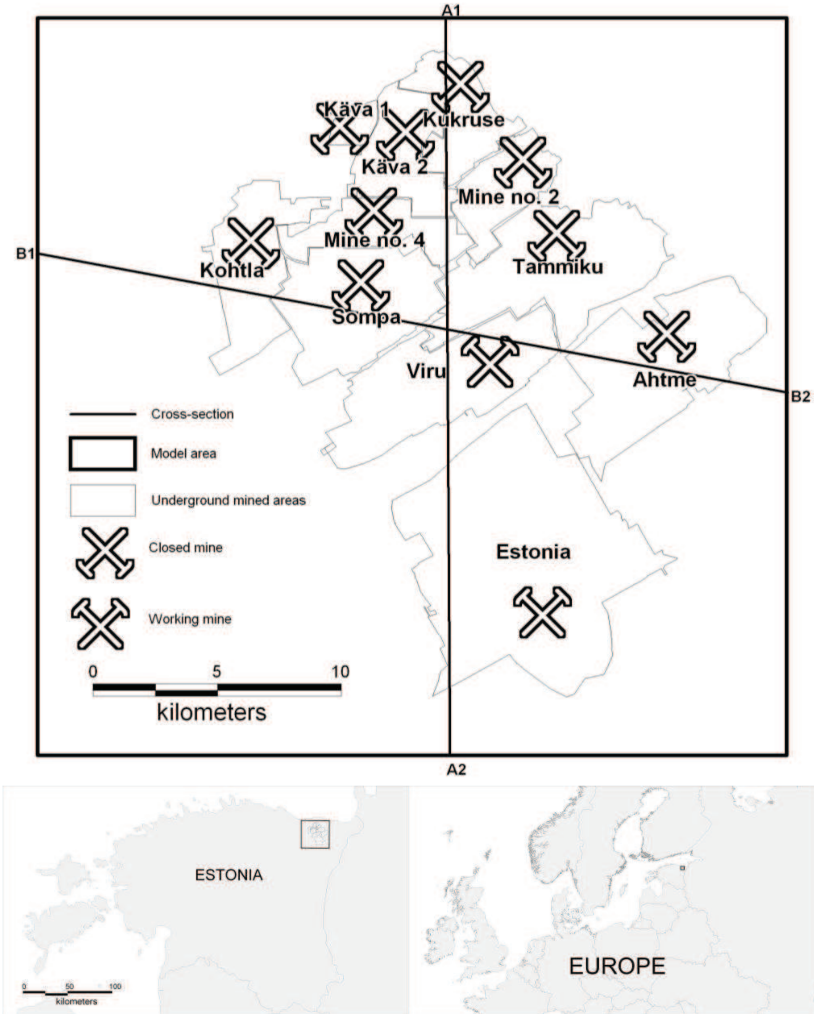

Figure 1 Underground oil shale mining area, its location in Estonia and in Europe

3.1. Groundwater

Groundwater accumulation in sedimentary rocks is possible due to fissures. Fissures in sedimentary rocks determine the main properties of the rock, such as hydraulic conductivity, permeability, specific storage and yield. Also strength properties of rocks depend on fissures [8].

The amounts of water in fissures depend on the season. Temperature of the water depends in active circulation belts mostly on air temperature and temperature of groundwater depends on geological conditions and bedding depth [8].

Aquifer horizontal hydraulic conductivity, aquitard vertical hydraulic conductivity, aquifer ratio of vertical and horizontal hydraulic conductivity, rock-specific yield and artesian storativity depend on the material and layer thickness [7].

The permeability of a porous medium is the ease with which a fluid can flow through that medium. It depends on the physical properties of the porous medium - grain size, grain shape, arrangement and pore interconnections. Water permeability is largely affected by the geological disturbance of the Earth crust, which makes the aquifer highly anisotropic [4]. The permeability of rocks is determined by the size of the pores between the rock particles [9]. If the rock has small pores, water cannot easily infiltrate into the rock and this means that the rock is impermeable. On the other hand, if the rock has large pores, water can easily infiltrate and thus the rock is permeable. When water flows through an area of impermeable rock, little water infiltrates the ground, as a result there is high surface runoff and leads to a high volume of flow of water [3].

Water quality is also important, because sulphate content value varies widely. The sulphate content in the water filling up mine is high; in the closed mines it is low [5,6].

During the pumping from underground mines depression cone formes around mining areas. The quantity of pumped out water from mines depends highly on the amount of precipitation and also less from groundwater and the water infiltrating from closed mines. According to the measurements and calculations performed, precipitation accounts for up to 70% of the water pumped out of mines [2, 4]. If the hydraulic conductivity of the streambed is high, the cone of depression may extend only partway across the stream. If the hydraulic conductivity of the streambed is low, the cone of depression may expand across and beyond the stream [7]. There are two water levels in ground – dynamic and static water level. Dynamic water level is level that forms during continuous pumping. Static water level is initial natural water level.

3.2. Rock parameters

The moisture content is the ratio of the weight of water in the sample to the weight of solids. Degree of saturation (saturation index) is usually expressed with the saturation index which is the percentage of sample voids filled with water. Effective porosity is the volume of interconnected voids that allow free water flow divided by the total sample volume [7].

Table 1 Representative porosity values for sedimentary rocks [7]

Rock type	Porosity (%)
Sandstone	14-49
Siltstone	21-41
Claystone	41-45
Shale	1-10
Limestone	7-56
Dolomite	19-33
Moraine	25-40

Effective porosity (Table 1), vertical and horizontal hydraulic conductivity (Table 3) and permeability are hydrogeological parameters that greatly depend on the size of sediment grains and the percentage of various sediment fractions. The porosity is given as the ratio of volume of voids to the total initial volume of the specimen before drying, which includes both voids and solids. For example average porosity of sandstone is 10%, sands 35% and clay 50% [8]. Generally if water content increases, the porosity increases. If water content decreases, the porosity decreases.

Hydraulic conductivity is dependent on properties of both the porous medium and the fluid. Hydraulic conductivity (K) is defining the specific discharge of a porous medium under a unit hydraulic gradient - $q=KI$. Hydraulic gradient (I) is hydraulic head loss per distance - $I=dh/dl$. Mostly horizontal conductivity is 10-100 times higher than vertical conductivity [10].

Specific storage (S_s) is volume of water released from storage from a unit volume of aquifer per unit decline in hydraulic head. Specific yield (S_y) is volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table. Specific yield is dimensionless value [7]. Transmissivity (T) is the product of hydraulic conductivity and saturated thickness - $T=Kb$.

4. Limits for locating energy spots

The areas, underground workings or outflows where energy could be extracted could be called as energy spots. For locating the energy spots following limiting factors should be taken into account and spatial query applied. These are: water protection areas, environmental protection areas, techno communication, restricted zones and areas and other objects.

Table 2 Specific water yield of common rocks [7]

Material	Specific Yield (%)
Silt	20
Clay	6
Limestone	14
Gravel, corase	21
Gravel, medium	24
Gravel, fine	28
Sand, coarse	30
Sand, medium	32
Sand, fine	33
Sandstone, fine grained	21
Sandstone, medium grained	27

5. Results

As the result of mapping, modelling and simulating, base for geometrical model, groundwater model and subsidence model was constructed. Geometrical model shows higher storage in underground abandoned mining area, where water flows towards wings of the oil shale deposit. Due to abandoning water level has risen recently in central northern part (Figure 2 and Figure 3).

Table 3 Representative horizontal hydraulic conductivity values [7]

Rock	Horizontal hydraulic conductivity (m/d)	Vertical hydraulic conductivity (m/d)
Gravel	$4.075x10^1$ - $1.223x10^3$	
Limestone	$8.15x10^{-4}$ - $8.15x10^2$	
Sand and gravel	8.15x10 - $2.038x10^2$	
Sandstone	$4.075x10^{-1}$-$2.038x10^1$	
clay	$8.15x10^{-1}$ - $8.15x10^{-2}$	$2.038x10^{-5}$- $4.075x10^{-4}$
shale	$4.075x10^{-7}$ - $4.075x10^{-3}$	$4.075x10^{-9}$ - $4.075x10^{-5}$
Clay, sand and gravel		$8.15x10^{-4}$ - $2.445x10^{-3}$
Sand, gravel and clay		$4.075x10^{-3}$ x $4.075x10^{-2}$

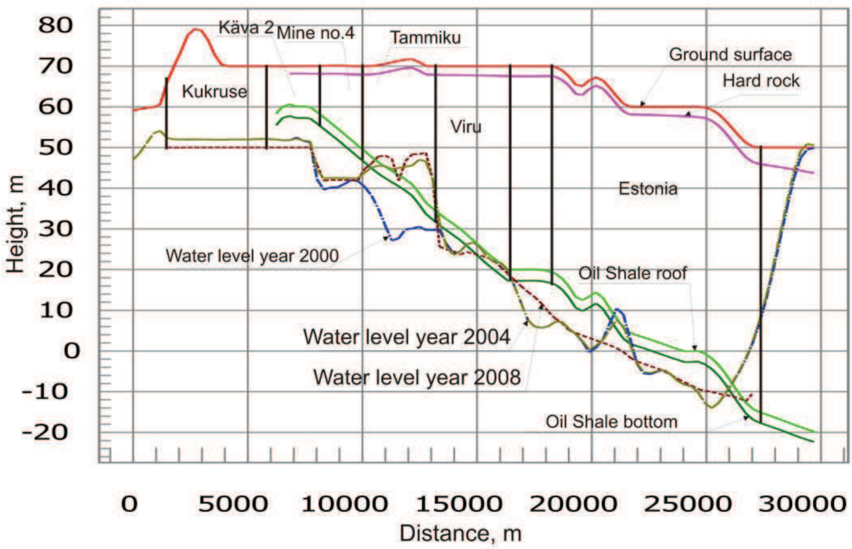

Figure 2 North-South cross section A1-A2of underground mining area (Figure 1)

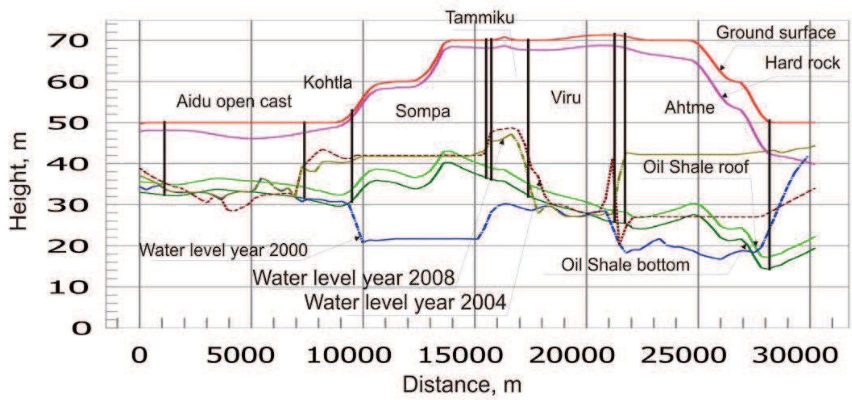

Figure 3 West-East cross section B1-B2 of mining area (Figure 1)

6. Geometrical and hydrological properties of the waterbody

After grid calculation initial data for base model shows that average thicknesses of oil shale is 2,5 m, varying from 1,5 to 3,2 meters. Thickness of overlaying rocks varies from 6 to 15 meters (Table 5). Geometrical model inserted into ModFlow model allows inserting properties into layers (Figure 4). In examining the properties of rocks and ModFlow modelling principles can select the parameters that enter the model, see the table (Table 6).

Using the properties of rocks and mining technologies is the result of differences in the calculation spreadsheet model, which consists of three parts. The first part takes into account the characteristics of the rock (porosity) and calculates how much water can be on top of oil shale layers (Quaternary and limestone overburden). The second part takes into account the extraction technology and to give an idea of how much water can be closed oil shale layers in mines. The third part shows how much water is capable to interchangeable between working and closed mines. Explanations, see the table below (Table 4).

Table 4 Water capacity in study area

Water capacity, million m^3	All mines*
In Quternary	336.3
In limestone overburden	365.0
In oil shale layers	227.5**
Summary	928.8

* Mines: Kukruse, Mine no 2, Käva no 1, Käva no 2, Mine no 4, Tammiku, Sompa, Kohtla, Ahtme, Viru, Estonia

** Without Viru and Estonia mine, therefore they are working mines and water is pumped out

Table 5 Data of mines that is located in the area, thicknesses of oil shale, overburden and height of surfaces

	Overburden thickness, m			Oil shale thickness, m			Water level year 2000, m			Water level year 2004, m			Water level year 2008, m			Groung surface, m		
Mine	min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max
Tammiku	11	23	43	2,8	2,8	2,8	25	35	42	35	48	51	28	45	47	50	67	80
Kukruse	9	11	12	2,8	2,8	2,9	51	52	54	49	50	50	51	52	58	60	71	79
Mine no. 2	9	13	22	2,8	2,8	2,8	39	46	52	49	50	51	43	47	52	58	70	76
Mine no. 4	4	12	20	2,8	2,8	2,8	21	39	48	41	42	50	41	42	48	50	62	73
Sompa	12	23	34	2,7	2,8	2,8	20	23	39	41	42	45	33	42	45	50	62	71
Viru	32	42	50	2,7	2,8	2,8	11	24	37	17	26	50	11	25	45	57	69	72
Estonia	49	57	66	2,6	2,7	2,8	-15	1	52	-18	-1	26	-15	1	42	50	63	70
Kohtla	3	15	54	2,7	2,8	2,8	22	35	44	38	42	44	31	41	47	50	51	60
Käva 1	15	21	30	2,8	2,8	2,8	49	51	53	50	50	51	51	52	52	52	60	62
Käva 2	7	10	13	2,8	2,8	2,8	41	51	53	44	50	51	43	51	52	59	66	78
Ahtme	13	37	55	2,8	2,8	2,8	8	20	35	18	27	29	19	42	45	42	64	71

Table 6 Parameters for hydrogeological model in ModFlow

Rock	Horizontal hydraulic conductivity	Vertical hydraulic conductivity	Porosity (%)	Specific Yield (%)
Limestone	$8.15\text{x}10^{-4}$ - $8.15\text{x}10^{-2}$	$8.15\text{x}10^{-6}$ - $8.15\text{x}10^{-4}$	7-56	14
clay	$8.15\text{x}10^{-1}$ - $8.15\text{x}10^{-2}$	$2.038\text{x}10^{-5}$- $4.075\text{x}10^{-4}$	41-45	6
shale	$4.075\text{x}10^{-7}$ - $4.075\text{x}10^{-3}$	$4.075\text{x}10^{-9}$ - $4.075\text{x}10^{-5}$	1-10	

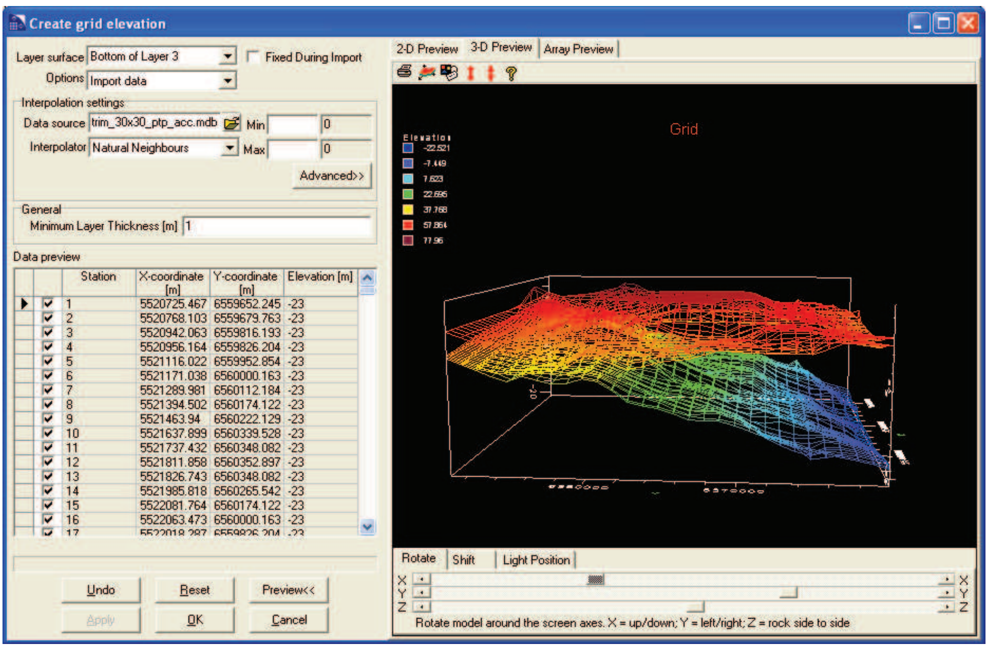

Figure 4 Geometrical base model for hydrogeological model

7. Conclusions

Technological and hydrogeological modelling allows calculating amount of water in the mines. Nevertheless, free flow in underground workings depends on the subsidence and closing practice in mines that needs to be checked by pumping tests. Oil shale from the mines pumped out the water is still, as it is required to mine oil shale. The study is ongoing and, if possible, existing pump stations can be used. The study area is nearly a billion cubic meter of water, heat carrier which can be exploited.

8. Acknowledgments

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PAPER VI **Karu, V.**; Robam, K.; Valgma, I. (2012). Potential usage of underground minewater in heat pumps. Estonian Geographical Society. “Estonia. Geographical Studies 11”. Raukas, A.; Kukk, K.; Vaasma, T. (Ed.). In print.

POTENTIAL USAGE OF UNDERGROUND MINEWATER IN HEAT PUMPS

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Introduction

Estonian oil shale deposit comprises ten closed mines that are fully or partly filled with water. Eight mines in the central part of the deposit: Ahtme, Kohtla, Kukruse, Käva, Sompa, Tammiku, mine No. 2 and mine No. 4 form one water body. Ubja mine and Kiviõli mines are located in the western part of the deposit, away from other mines.

In Estonia 9 TWh of heat is produced an average in a year for district heating network. Heat production differs in summer and winter about five times (Statistics Estonia, 2010). In eastern part of Estonia, where closed oil shale mines are located, it would be useful to get one part of heat from water. Water has a certain temperature throughout the year. To receive the heat from minewater we have to use heat pump (Leonardo Energy, 2008; Estonian Heat Pump Association, 2010). First heat pump, based on minewater started working in Kiikla settlement in 2011 (Karu, 2011). The main aim of this research is to find parameters of water and its media that influence amount and availability of energy in Estonian oil shale underground mining area and analyze the situation of possible minewater usage as heat source in heat pumps.

Oil Shale mining area

Underground oil shale mining has been performed for 90 years in the middle-north part of the Estonian deposit (Figs. 1, 2 and 10). The depth has been lower in central-northern part, thickness and quality has been greater in the same area. This was the reason why in 1916 mining started from Kukruse moving toward the wings of the deposit where mining conditions worsen. In northern part of the deposit mostly hand-mining technology and longwall mining was used (Fig. 1) and in newer mines from 1950–1960s mostly room and pillar mining method has been used (Fig. 2).

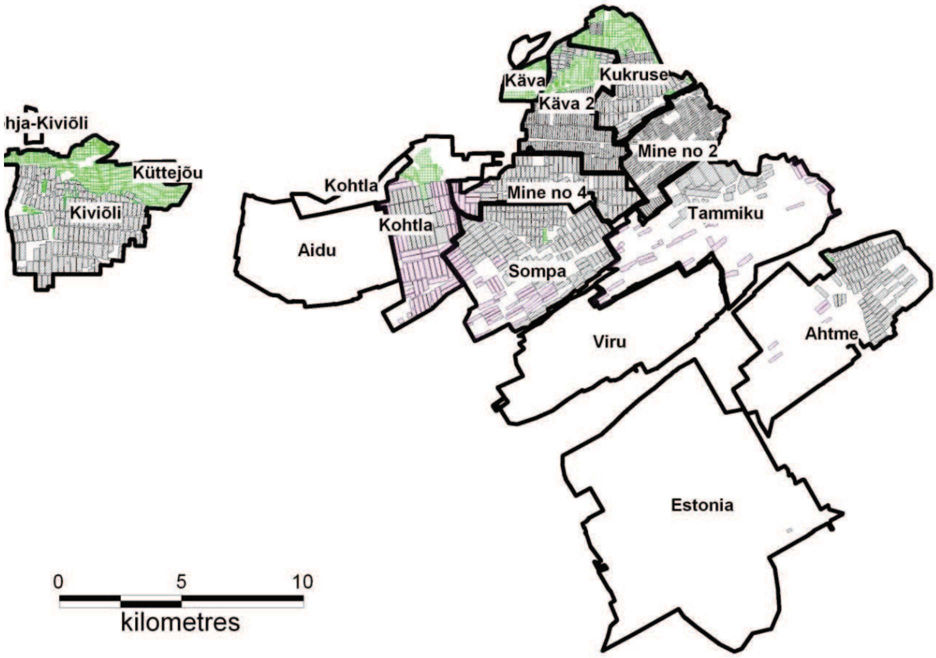

Fig. 1. Hand-mined (longwall, rooms) and mechanised longwall mining areas.

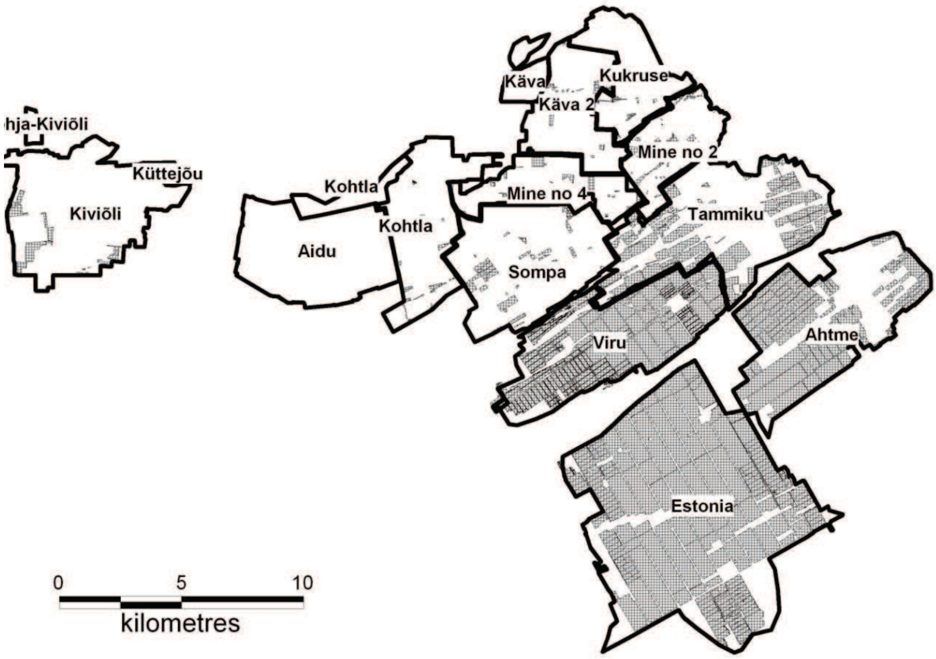

Fig. 2. Room and pillar mining areas.

Groundwater

Groundwater accumulation and moving in sedimentary rocks is possible due to fissures. Fissures in sedimentary rocks determine the main properties of the rock, such as hydraulic conductivity, permeability, specific storage and specific yield. Also strength properties of rocks depend on fissures (Ojaste, 1974). The amounts of water in fissures depend on the season. Temperature of the water depends in active circulation belts mostly on air temperature and temperature of groundwater depends on geological conditions and bedding depth (Ojaste, 1974). The quality of the water in closed mines is improving. The content of sulphates and iron in mine water decreases and in about five years after the closure of the mine is below the maximum level permitted in drinking water (Erg, 2005; Reinsalu et al., 2006; Karu, 2010).

Aquifer horizontal hydraulic conductivity, aquitard vertical hydraulic conductivity, aquifer ratio of vertical and horizontal hydraulic conductivity, rock-specific yield and artesian storativity depend on the material and layer thickness (Walton, 1987). The permeability of a porous medium is the ease with which a fluid can flow through that medium. It depends on the physical properties of the porous medium - grain size, grain shape, arrangement and pore interconnections. Water permeability is largely affected by the geological disturbances of the Earth crust, which makes the aquifer highly anisotropic (Reinsalu et al., 2006). The permeability of rocks is determined by the size of the pores between the rock particles (Walton, 1987; Permeability of rocks, 2010). If the rock has small pores, water can not easily infiltrate into the rock and this means that the rock is impermeable. On the other hand, if the rock has large pores, water can easily infiltrate and thus the rock is permeable. When water flows through an area of impermeable rock, little water infiltrates in the ground, as a result there is high surface runoff and leads to a high volume of flow of water (Kresic, 1997; Permeability of rocks, 2010). Water quality is also important, because sulphate content value varies widely. The sulphate content in the water filling up mine is high; in the closed mines it is low (Erg et al., 2007; Statistics Estonia, 2010). During the pumping from underground mines depression cone formes around mining areas. The quantity of pumped out water from mines depends highly on the amount of precipitation and less from groundwater and the water infiltrating from closed mines. According to the measurements and calculations performed, precipitation accounts for up to 70% of the water pumped out of mines (Reinsalu et al., 2006; Robam & Valgma, 2010). If the hydraulic conductivity of the streambed is high, the cone of depression may extend only partway across the stream. If the hydraulic conductivity of the streambed is low, the cone of depression may expand across and beyond the stream (Walton, 1987). There are two water levels in ground – dynamic and static water level. Dynamic water level is level that forms during continuous pumping. Static water level is initial natural water level.

Rock parameters

The moisture content is the ratio of the weight of water in the sample to the weight of solids. Degree of saturation (saturation index) is expressed with the saturation index which is the percentage of sample voids filled with water. Effective porosity is the volume of interconnected voids that allow free water flow divided by the total sample volume (Walton, 1987). Effective porosity (Table 1), vertical and horizontal hydraulic conductivity (Table 2) and permeability are hydrogeological parameters that greatly depend on the size of sediment grains and the percentage of various sediment fractions. The porosity is given as the ratio of volume of voids to the total initial volume of the specimen before drying, which includes both voids and solids. For example average porosity of sandstone is 10, sands 35 and clay 50% (Ojaste, 1974). Generally if water content increases, the porosity increases. If water content decreases, the porosity decreases.

All these properties (Table 1–4) are not the same in the mined out area. They can be used in accordance with the mining method that was used (Figs. 3 and 4) and therefore the used mining technology has to be known.

Table 1

Representative porosity values for sedimentary rocks (Walton, 1987)

Rock type	Porosity (%)
Sandstone	14–49
Siltstone	21–41
Claystone	41–45
Shale	1–10
Limestone	7–56
Dolostone	19–33
Till	25–40

Table 2

Representative horizontal and vertical hydraulic conductivity values (Walton, 1987)

Rock	Horizontal hydraulic conductivity (m/d)	Vertical hydraulic conductivity (m/d)
Gravel	$4.075x10^{1}$–$1.223x10^{3}$	
Limestone	$8.15x10^{-4}$–$8.15x10^{2}$	
Sand and gravel	8.15x10–$2.038x10^{2}$	
Sandstone	$4.075x10^{-1}$–$2.038x10^{1}$	
Clay	$8.15x10^{-1}$–$8.15x10^{-2}$	$2.038x10^{-5}$–$4.075x10^{-4}$
Shale	$4.075x10^{-7}$–$4.075x10^{-3}$	$4.075x10^{-9}$–$4.075x10^{-5}$
Clay, sand and gravel		$8.15x10^{-4}$–$2.445x10^{-3}$
Sand, gravel and clay		$4.075x10^{-3}$–$4.075x10^{-2}$

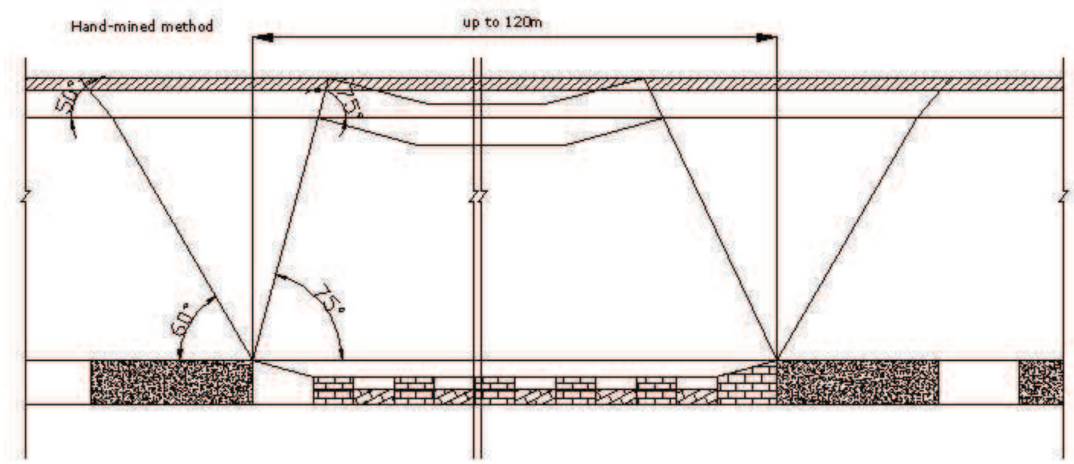

Fig. 3. Cross section of hand mining technology.

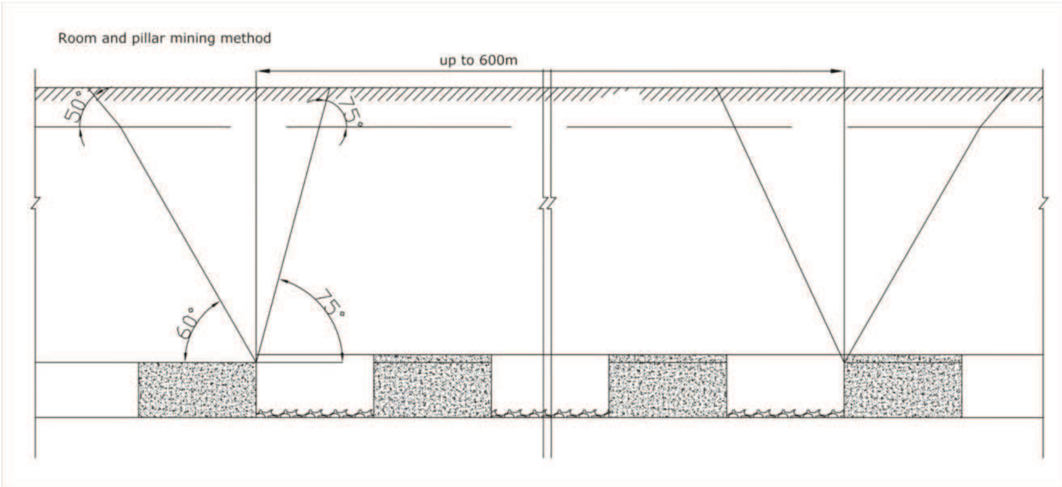

Fig. 4. Cross section of room and pillar mining technology.

Hydraulic conductivity depends on properties of both the porous medium and the fluid. Hydraulic conductivity (K) is defining the specific discharge of a porous medium under a unit hydraulic gradient - q=KI. Hydraulic gradient (I) is hydraulic head loss per distance - I=dh/dl. Mostly horizontal conductivity is 10–100 times higher than vertical conductivity (Perens, 2009). Specific storage (S_s) is volume of water released from storage from a unit volume of aquifer per unit decline in hydraulic head. Specific yield (S_y) is volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table (Table 3). Specific yield is dimensionless value (Walton, 1987). Transmissivity (T) is the product of hydraulic conductivity and saturated thickness - T=Kb.

Table 3

Specific water yield of common rocks (Walton, 1987)

Material	Specific yield (%)
Silt	20
Clay	6
Limestone	14
Coarse gravel	21
Medium gravel	24
Fine gravel	28
Coarse sand	30
Medium sand	32
Fine sand	33
Fine grained sandstone	21
Medium grained sandstone	27

As the result of mapping, modelling and simulating, base for geometrical model, groundwater model and subsidence model were constructed. Geometrical model shows higher storage in underground abandoned mining area, where water flows towards wings of the oil shale deposit. Water level has risen recently in central northern part (Valgma et al., 2010).

Methods

For calculating potential amount of water the underground space and its properties should be defined. Since underground space forms from mine workings, roof structure and related water channels or tubes, this situation has to be mapped in 3D. Hydrogeological parameters have to be created and evaluated for defining underground space properties and classification of used mining technologies. Classification helps defining space that is available for water in abandoned mines.

Main tools for analyzing amount of water in abandoned oil shale mines is computational modelling with spreadsheet models and designing the water flow with ModFlow. For the computational modelling we need to know how oil shale bed has mined (mining technology), how much space is in the old mine drifts and how water is moving between the mines. The model enables to assess the water levels in different mines and their border areas and to make assumptions and predictions about the water movement directions (Reinsalu et al., 2006).

Geometrical and hydrological properties of the waterbody

The geometrical parameters for the model are oil shale seam bottom height, roof height, length, width and height of pillars and workings in the mines, thickness of overburden that is divided into required number of sublayers by different storativity values. The main tools chosen for spatial modelling were spreadsheets and MS Access databases for systemising and querying data, MapInfo for georeferencing, Vertical Mapper for interpolating and grid calculations and Modflow for pumping simulation. With help of interpolated grids, surface elevations (Fig. 5), layer thicknesses and required properties were calculated. Modelled result shows that flat oil shale layer bottom sloping to south (Fig. 6). Rapid changes in elevation show geological fault zones (Fig. 6).

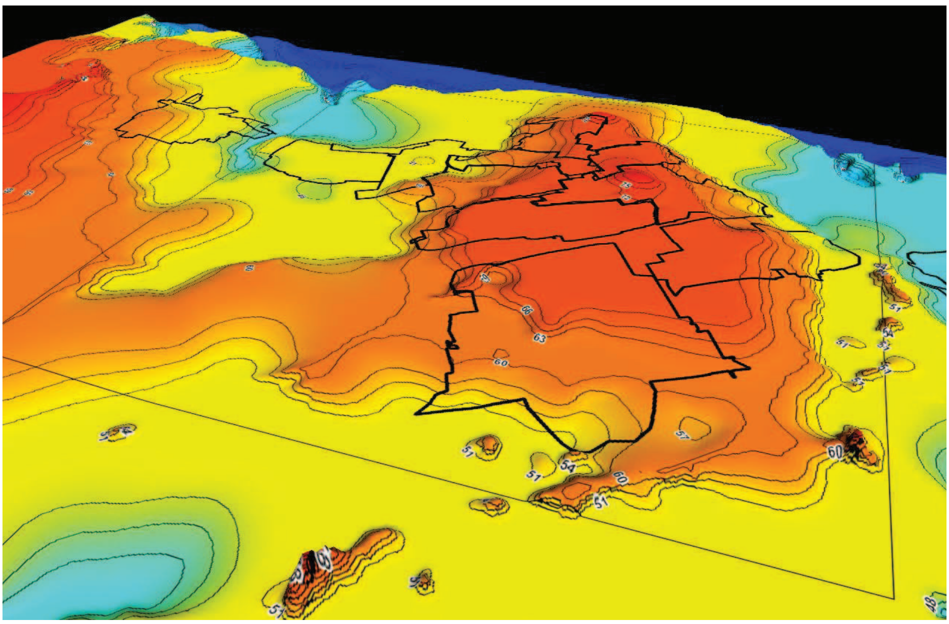

Fig. 5. Surface of the study area.

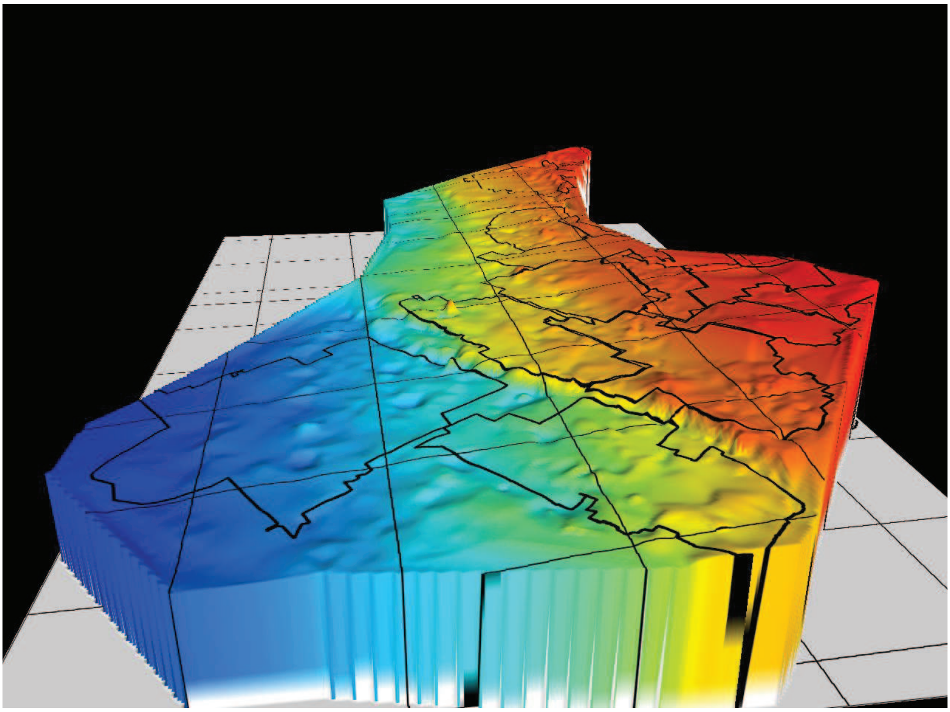

Fig. 6. Oil Shale layer is flat and lowers 3 meter per kilometer.

After grid calculation initial data for base model shows that average thicknesses of oil shale is 2.5 m, varying from 1.5 to 3.2 meters. Thickness of overlaying rocks varies from 6 to 66 meters (Table 4).

Since hydrogeological situation has been changed relatively fast due to closing down several mining operations and stopping pumping in these regions, dynamic model has to be created, simulating groundwater level, amount of water in working and abandoned underground mines and potential productivity of wells starting to operate for energy extraction. Main hydrogeological parameters for hydrogeological model are porosity, vertical and horizontal hydraulic conductivity, infiltration rate, storage and information about water aquifers. Dynamic model must be checked with a spreadsheet as well as the amount of water to find the study area, using the same parameters to be entered in the hydrogeological ModFlow model (Table 5; Fig. 7).

Table 4

Data of mines that are located in study area, thicknesses of oil shale, overburden and height of surfaces

Mine	Overburden thickness, m			Oil shale thickness, m			Ground surface, m		
	min	avg	max	min	avg	max	min	avg	max
Tammiku	11	23	43	2.8	2.8	2.8	50.0	67.4	80.0
Kukruse	9	11	12	2.8	2.8	2.9	59.9	70.5	79.5
Mine no. 2	9	13	22	2.8	2.8	2.8	58.2	70.0	75.9
Mine no. 4	4	12	20	2.8	2.8	2.8	49.9	61.7	72.5
Sompa	12	23	34	2.7	2.8	2.8	50.0	62.1	71.5
Viru	32	42	50	2.7	2.8	2.8	57.0	69.4	72.0
Estonia	49	57	66	2.6	2.7	2.8	50.0	63.4	70.0
Kohtla	3	15	54	2.7	2.8	2.8	49.8	51.1	60.0
Käva 1	15	21	30	2.8	2.8	2.8	51.8	59.5	62.0
Käva 2	7	10	13	2.8	2.8	2.8	58.9	66.1	77.8
Ahtme	13	37	55	2.8	2.8	2.8	42.3	63.8	71.2
Mine	Water level year 2000, m			Water level year 2004, m			Water level year 2008, m		
	min	avg	max	min	avg	max	min	avg	max
Tammiku	25.1	35.4	41.8	34.9	47.8	51.1	28.2	45.0	47.4
Kukruse	51.0	52.1	53.9	49.4	50.0	50.1	51.2	52.1	57.7
Mine no. 2	39.2	45.9	51.8	49.2	50.0	51.5	42.6	46.8	51.9
Mine no. 4	21.0	39.2	47.5	40.9	42.0	49.7	41.0	42.5	47.8
Sompa	19.8	22.6	38.7	41.4	42.0	45.0	32.6	41.8	45.0
Viru	11.5	24.0	37.0	17.3	26.4	50.0	11.3	24.6	44.8
Estonia	-15.0	1.0	52.2	-18.5	-0.8	25.6	-15.1	0.6	41.5
Kohtla	22.2	34.9	44.2	37.8	41.6	44.4	30.8	40.7	47.5
Käva 1	49.4	51.4	53.3	49.7	50.0	50.5	50.5	51.5	52.1
Käva 2	40.8	51.3	52.7	43.8	50.0	50.8	43.2	51.3	52.4
Ahtme	7.8	20.5	34.8	18.1	26.8	28.6	19.4	42.0	45.1

Table 5

Parameters for hydrogeological model in ModFlow

Rock	Horizontal hydraulic conductivity (m/d)	Vertical hydraulic conductivity (m/d)	Porosity (%)	Specific yield (%)
Limestone	$8.15x10^{-4}$–$8.15x10^{-2}$	$8.15x10^{-6}$–$8.15x10^{-4}$	7–56	14
clay	$8.15x10^{-1}$–$8.15x10^{-2}$	$2.038x10^{-5}$–$4.075x10^{-4}$	41–45	6
Oil shale	$4.075x10^{-7}$–$4.075x10^{-3}$	$4.075x10^{-9}$–$4.075x10^{-5}$	1–10	

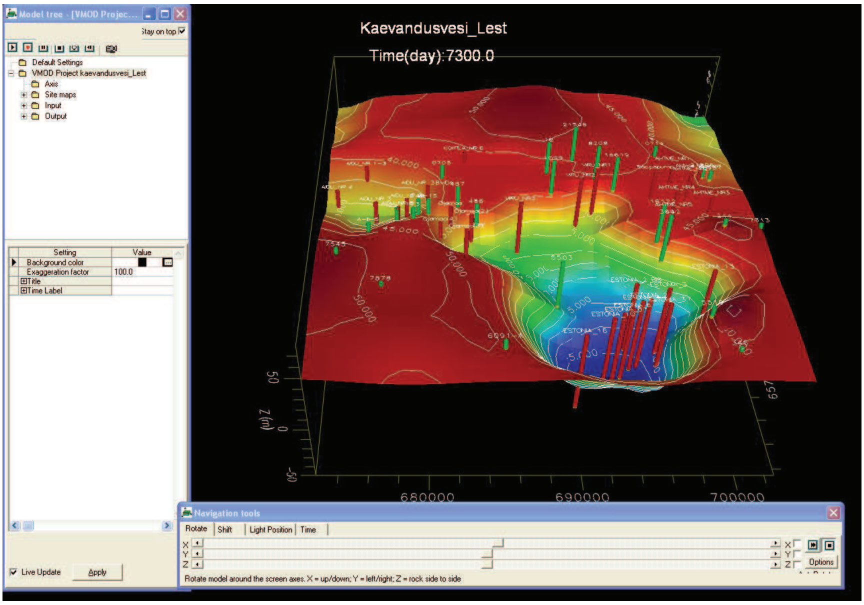

Fig.7. Screen shot of Dynamic water flow model of minewater.

Limits for locating energy spots

The areas, underground workings or outflows where energy could be extracted could be called as energy spots. For locating the energy spots following limiting factors should be taken into account and spatial query applied. These are: water protection and environmental protection areas, techno communication, restricted zones and areas and other objects.

Heat source calculations

Heat can be defined as energy transferred between matters because of differences in temperature. The ability of matter to transfer heat depends on its mass and temperature. In this research primarily analytical tools are spreadsheet models and GIS data analysis tools.

To calculate transfers of heat energy, following equation can be used:

$$Q = m \cdot c \cdot \Delta t \,(\mathrm{kW}) \qquad (1)$$

where:

Q – heat absorbed or released (kW)

m – water mass (kg/s);

c – specific heat capacity (4,19 kJ/kgK for water);

Δt – change in temperature (^{o}C)

To analyze the situation, water volume for heat pump has to be known, in addition to the degrees of the temperature that will be decreased in heat pump and coefficient of performance (COP) (Calculating COP, 2010), where:

- Water volume for heat pump – amount of water that is pumped through heat pump (m^3/h).
- Change in temperature – it depends on how much heat will be taken away from water (^{o}C)
- Coefficient of performance (COP) – it depends on how much electricity the heat pump complex consumes.

Water volume and change in temperature are inter-dependent. Then water can quickly heat up in earth's crust (if water is returned back to mine, it depends on the technological solution).

COP is a ratio of energy output to energy input. For instance, a COP of 1 means that for every one unit of energy that heat pump uses (such as 1 watt) it produces one unit of an equivalent unit of heat (1 watt of heat). A COP of 2 means the heat pump can produce twice as much heat as it takes in to work, discounting small expenditures in its motor. Normal heat pumps have COPs that range between 2 and 5 and depending on their efficiency. To know how much should be spent on electricity to get heat with heat pump, we have to know COP and then can be calculate the electricity needs, the equation is:

$$COP = \frac{Q_{heat\ out}}{Q_{electric\ in}} \tag{2}$$

where:

COP – coefficient of performance;

$Q_{heat\ out}$ – quantity of heat production by heat pump (kW); $Q_{electric\ in}$ – quantity of electricity for heat production (kW).

In study of underground water pools potential using heat pumps are analyzed in case the coefficient of performance is three (COP = 3).

Example of calculations for heat pumps

Minewater which is heat source for heat pumps must produce 10 MW heat. Initial water temperature is 8 ^{o}C and final water temperature is 7 ^{o}C (change in water temperature is 1 ^{o}C). To calculate the water mass, we have to transform the first equation to this equation:

$$m = \frac{\frac{Q}{c \cdot \Delta t}}{\rho} \tag{3}$$

where:

Q – heat absorbed or released (kW)

m – water mass (kg/s);

c – specific heat capacity (4,19 kJ/kgK for water);

Δt – change in temperature (^{o}C)

ρ – density of water (kg/m^3)

and calculation:

$$m = \frac{\frac{10000}{4{,}19 \cdot 1}}{1000} = 2{,}39\frac{m^3}{s} \Rightarrow 8604\frac{m^3}{h}$$

In order to produce 10 MW of heat, we need 8604 m^3/h minewater which is passing heat pump. Heat pumps use coefficient of performance three (COP = 3) $\frac{10000}{3} = 3333kW$, so it should be spent on electricity for 10 MW heat 3333 kW electricity.

Results

With spreadsheet model amount of water in different seams was calculated. Taking into account porosity and thickness of seams, water amount in top of oil shale layers was calculated. Used mining technology, oil shale layer thickness determine the free space in mine that would be filled with minewater (Table 6). Taking into account these factors, the amount of water in extracted oil shale layer has been calculated (Table 6). Result of calculations shows that the amount of water is the highest in Ahtme mine (Fig. 8; Table 6). Most of the water, which is located in the mining area is in the extracted oil shale seam (Fig. 9; Table 6).

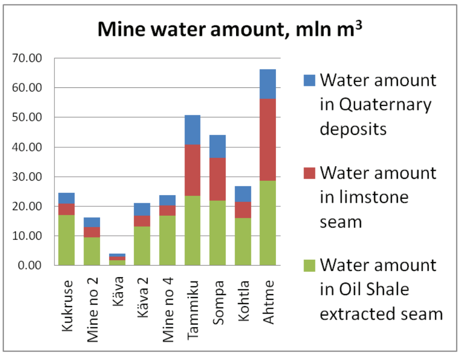

Fig. 8. Amounts of minewater.

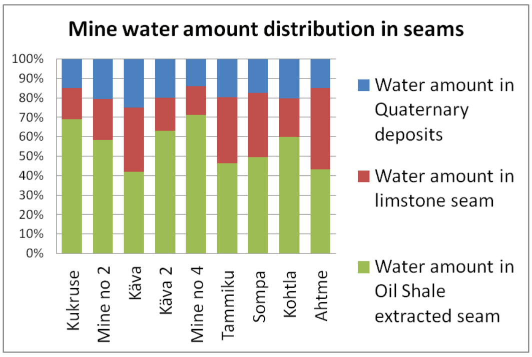

Fig. 9. Minewater amount distribution in seams.

Table 6

Minewater amount and properties in study area

Options	Kukruse	Mine no 2	Käva	Käva 2	Mine no 4	Tammiku	Sompa	Kohtla	Ahtme
Mine opening	1921	1949	1924	1924	1953	1951	1948	1937	1948
Mine closing	1967	1973	1972	1972	1975	1999	1999	2001	2001
Working time, year	46	24	48	48	22	48	51	64	53
Field area, km^2	13.20	12.30	3.47	14.05	12.70	40.00	33.60	18.30	43.30
Mined field area, km^2	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36
Not mined area, km^2	-1.93	3.73	1.63	2.33	2.27	20.74	15.46	6.16	16.94
Thickness of overburden, m	11	13	21	10	12	23	23	15	37
Thickness of oil shale seam, m	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Geological space in oil shale seam, mln m^3	**42.82**	**24.08**	**5.22**	**33.05**	**29.20**	**53.92**	**50.24**	**33.52**	**73.53**
Mined oil shale seam thickness, m									
Hand-mined face	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Hand- mined rooms	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Room and pillar	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Drifts	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Longwall face	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Mined field area, km^2									
Hand-mined face	11.28	6.87		9.16	7.71	4.36	12.70	3.80	6.33
Hand- mined rooms	3.50	0.00	1.84	1.73	0	0	0.06	1.36	0.05
Room and pillar	0.29	1.70		0.79	1.08	11.81	1.86	0.55	19.22
Drifts	0.06	0.00	0.00	0.04	0.69	0.36	0.00	0.02	0.30
Longwall face	0	0		0	0.95	2.74	3.52	6.41	0.46
Total mined area	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36
Mine water amount, mln m^3									
Water amount in Quaternary deposits	3.66	3.37	1.04	4.19	3.34	9.94	7.76	5.48	9.96
Water amount in limstone seam	3.94	3.40	1.37	3.56	3.47	17.32	14.46	5.30	27.61
Water amount in Oil Shale extracted seam	17.05	9.54	1.74	13.29	16.92	23.51	21.93	16.14	28.75
Total	**24.65**	**16.30**	**4.14**	**21.04**	**23.74**	**50.77**	**44.15**	**26.91**	**66.32**
Mine water amount distribution in seams, %									
Water amount in Quaternary deposits	14.8	20.7	25.0	19.9	14.1	19.6	17.6	20.4	15.0
Water amount in limstone seam	16.0	20.8	33.0	16.9	14.6	34.1	32.7	19.7	41.6
Water amount in Oil Shale extracted seam	69.2	58.5	42.0	63.2	71.3	46.3	49.7	60.0	43.3

Water requirements for heat pump

Possible location of heat pump should be on the top of the Ahtme oil shale mine (Fig. 10). Possible location is near Ahtme thermal power plant. Heat pump would use Ahtme underground water pool for heat production. Amount of minewater in Ahtme mine is 69 mln m^3. Heating consumption are 10 MW in summer and 50 MW in winter. Knowing the required heating capacity and using equations one and three, spreadsheet model is used for calculating the necessary water requirements for heat pump (Table 7).

Table 7

Water requirements depend on the heat production and temperature reduction

Heat requirement, MW	Change in temperature , ^{O}C	Initial water temperature, ^{O}C	Final water temperature after heat pump, ^{O}C	Water requirements, m^3/h
10	1	8	7	8 604
10	2	8	6	4 302
10	3	8	5	2 868
10	4	8	4	2 151
50	1	8	7	43 021
50	2	8	6	21 511
50	3	8	5	14 340
50	4	8	4	10 755

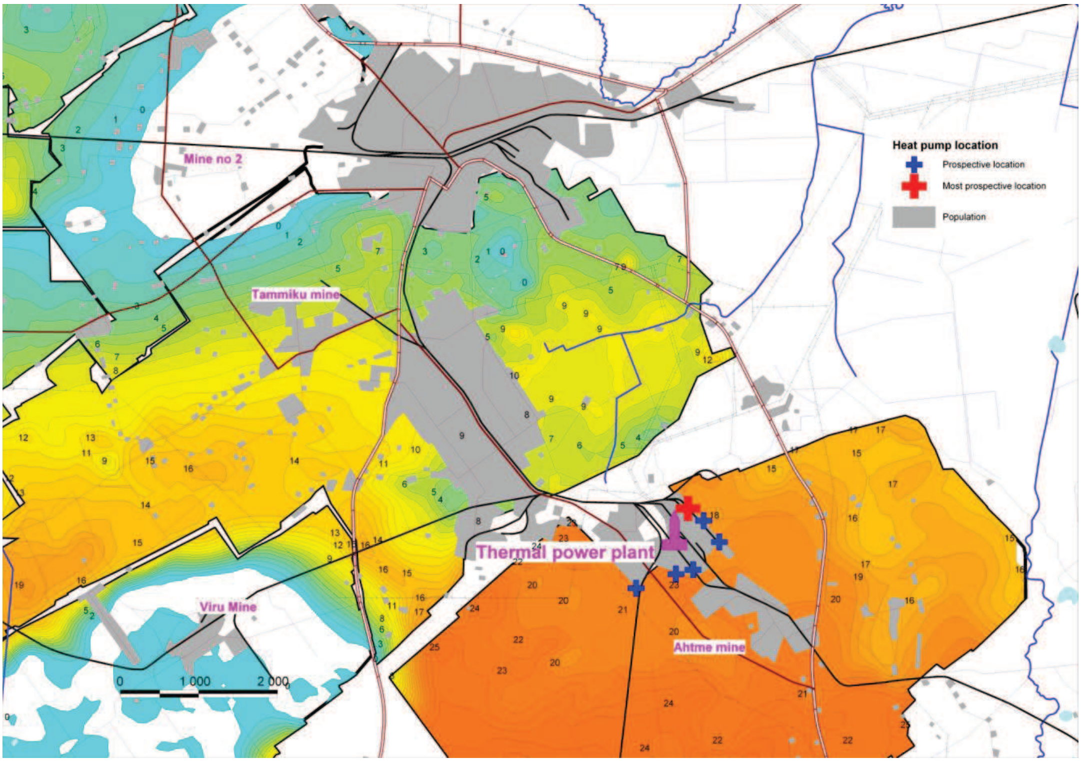

Fig. 10. Prospective locations for heat pump in Jõhvi and Ahtme area, figures show the height of the water from the bottom of the oil shale seam.

Technological solution for using heat pump complex

Using minewater in heat pumps, the best possible technical solution is: pumping the water through drillhole onto the ground surface (Fig. 11). After lowering the temperature of minewater in heat pump about 1–4 degrees, the water will be directed back to the mine or to the water sourse. If we use underground water pools water then the recommendation temperature reduction must be at least four degrees. When temperature is lowered less, we have to use large volumes of minewater and that would change the land and pillar stability situation in the mine. Heat pump complex, which produces 10 MW of heat, uses 2151 m^3/h minewater, produces 87 650 MWh heat per year and 29 217 MWh of electricity is consumed (COP =3). Heat pump complex, which produces 50 MW of heat, uses 10 755 m^3/h minewater. The best possible solution would be to build 10 MW heat pump complex, this allows optimum heat production through the year. In winter will be necessary to use also thermal power plant for heat production. Best location for the heat pump is near the Ahtme thermal power plant, potential locations are shown in figure (Fig. 10). Then we can use an existing district heating network and if will be needed to increase the temperature in heating network we can use the thermal power plant.

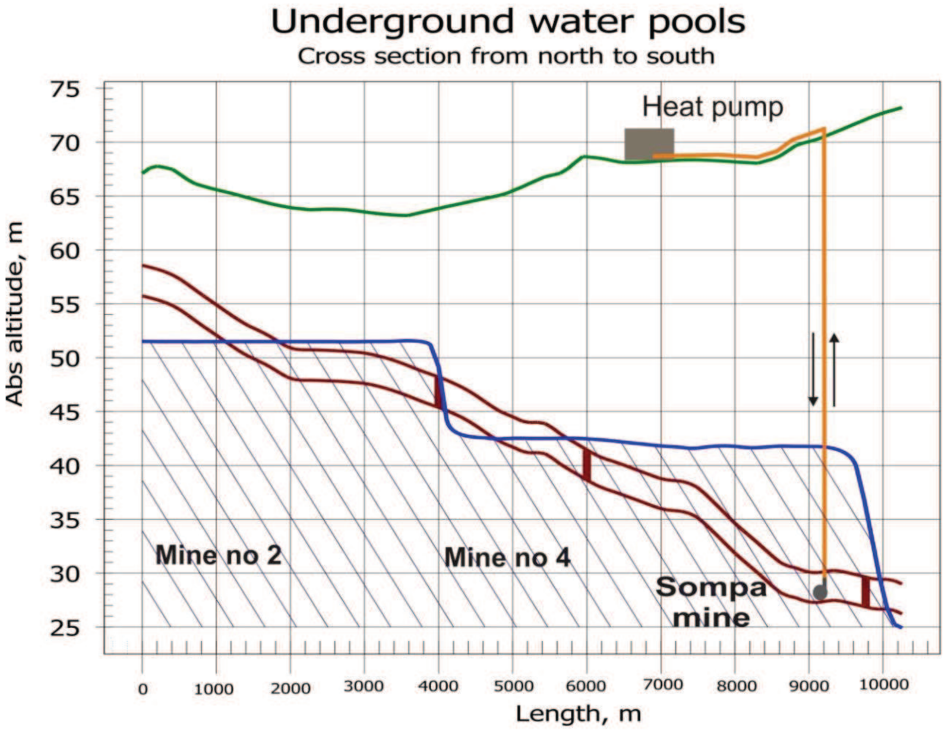

Fig. 11. North-south cross section of underground mining area and heat pump installation example.

Conclusion

Technological and hydrogeological modelling allows calculating amount of water in the mines. Nevertheless, free flow in underground workings depends on the subsidence and closing practice in mines that needs to be checked by pumping tests. Groundwater and underground pool water can be used as heat source for heat pump complex.

In areas where groundwater is abundant and easily accessible, groundwater is extracted from a well and circulated through the cold side of the heat pump. Groundwater can be used either directly via circulation through the evaporator or indirectly via the use of an intermediate heat exchanger. An intermediate heat exchanger is the preferred choice in most cases, as groundwater may cause corrosion or clogging of the evaporator. After leaving the heat exchanger, the cold ground water will be directed back into the ground via an injection well.

In underground mines, which are filled with water the water has a stable temperature all over year. Subjected to a heat pump and returned into the water heats up when mixed with warmer water and heat of the earth. Using minewater for heat pump complex is unique in the world. First heat pump complex was opened in 2011 in Kiikla settlement.

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Increasing oil shale quality for meeting EU environmental requirements

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Abstract

In the future mining conditions of oil shale mining are worsening and environmental taxes will be increased. Higher quality and courser material is required for more effective usage of boiler and generator units in power stations and oil plants. At the same time decreasing ash and limestone amount in the process will lead to more sustainable industry. Solution for the mining industry is related to the optimal usage of technological resources, utilizing best available techniques and modeling and visualization of mining influences for explaining the changes in technology to the influenced parties. One of the solutions could be utilizing selective mining and backfilling. Related tests have shown good result and show promising future for sustainable oil shale mining.

Introduction

Environmental tax for CO2 and other influences to the nature like water and waste rock depositing increases. Natural worsening of mining conditions and increase of oil price as side product for Estonian electricity production are the reasons for research for technological changes in mining. Analyses of Estonian energy system have shown that increasing of the fuel quality in power stations could improve the issues of high CO2 emission ratio and at the same time increase effectiveness of power or oil generator units. Effect can be achieved in decreasing CO2 pollution, ash pollution and water pollution. To avoid a potential problem of non-utilizable waste in stockpiles of mine areas selective mining provides leaving non-conditional rock mass in mined-out underground areas.

Higher quality and courser material is required for more effective usage of boiler and generator units in power stations and oil plants. At the same time decreasing ash and limestone amount in the process will lead to more sustainable industry. For this purpose cutting tests of oil shale and limestone have been carried out in years 2005...2007 in Estonia. The tests have been performed in Väo Paas, Põhja Kiviõli, Paekivitoodete tehase, KNC Ubja, Aru Lõuna and Narva surface mines and in Estonia underground mines. Previously related tests have been executed in all Estonian oil shale mines. For the future backfilling and stability tests are in planning stage for underground mines. Mining of non traditional fuels in flat laying deposits is well developed in Estonia and BAT (Best Available Technology) developed here could be used for future deposits elsewhere.

Purpose of the study

The main purpose of the research analyse usage of BAT and criteria for selecting, planning and design of technological planning. Higher quality and courser material is required for more effective usage of boiler and generator units in power stations and oil plants. As the result of that to map possibilities of utilising BAT (best available technology), to create criteria, methods, bases for planning for choosing BAT for Estonian and similar mineral resources, to decrease the influence of mining to the environment, to improve mining environment and to decrease the opposition of the society for using minerals industry for economy. Partial purpose is finding and selecting the criteria and bases for BAT, decreasing losses of minerals and the influence to the environment of surface and underground oil shale mining. General purpose is optimising usage of mineral resources in economy, sustainable development of mining, land usage, resource and subsurface usage.

Hypothesis

The main hypothesis is related to the possibility of extracting minerals in populated areas with suitable technology with adequate cost. The criteria for solving the problems are minimum influence and cost, minimum influence to environment and social sphere, minimum waste and residue production and maximum benefit for society, economy, teaching and country. The oil shale breaking and crushing, separating and storing processes together with ash management are complex problems that have to be analysed together as one chain. Optimising these processes will lead to the sustainable usage of oil shale.

Methods

The main methods of the research are connected to tests of the application of sensors, measurement data and mining conditions, converting received data and using it for modelling. The methods are testing of application, cooperation, range of usability and suitability of mine planning software, laboratory and fieldworks for application of mining measurements equipment for modelling.

Due to environmental restrictions, social pressure and deeper bedding of oil shale in potential mining fields, testing of high-productive, environmentally friendly mechanical mining is needed for successful continuation of independent energy supply (oil shale) for Estonia. New flexible and powerful mining technology will guarantee securing independence of Estonian energy sector until establishing secure renewable energy production.

Selection of best technology

Selection of technology depends directly on economic figures, but in the stage when economic figures do not exist, the BAT criteria have to be used.

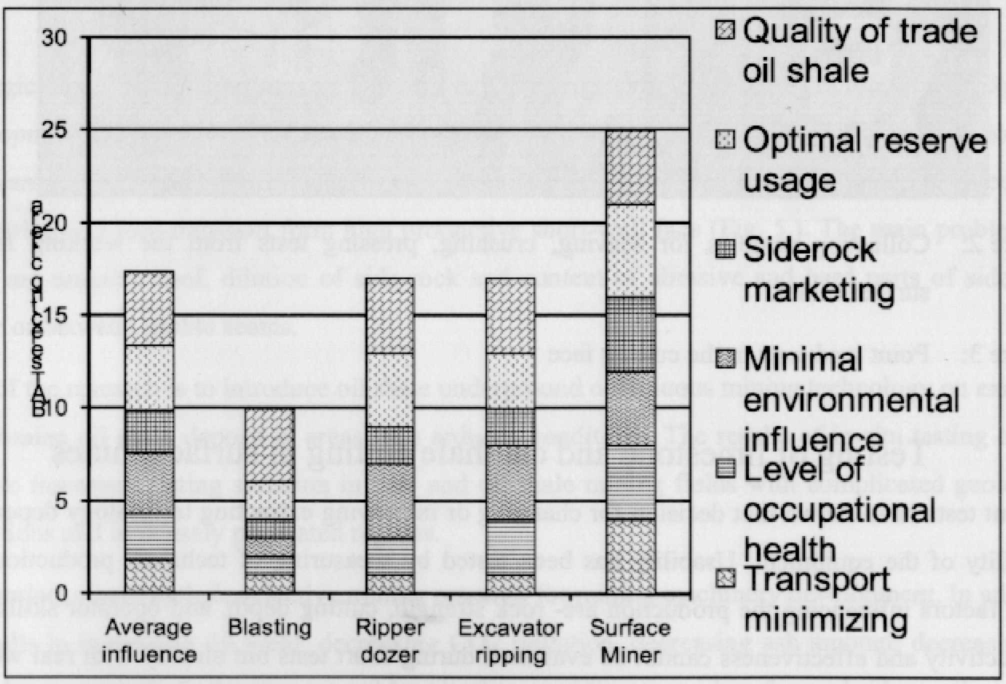

Figure 1: Selecting technology for testing by BAT criteria

Lately new technologies have been introduced and tested. These are surface miner tests in dolostone, limestone and oil shale.

Mechanical cutting

In the situation of constantly decreasing mining conditions the main ways of increasing output materials quality are selective mining or more effective processing after mining. The tests of mechanical mining have shown that selective mining with ripper – dozers have proved themselves but for decreasing losses, higher accuracy of cutting is needed. This has been tested with high selective cutting with surface miners (Fig. 4.).

Surface miner breaks, crushes and loads material in one operation. The size of particles of the cut extracted rock depends on milling depth, cutting resistance, compressive strengths and operating speed but usually it does not exceed 200 mm (Fig. 2. and Fig. 3.).

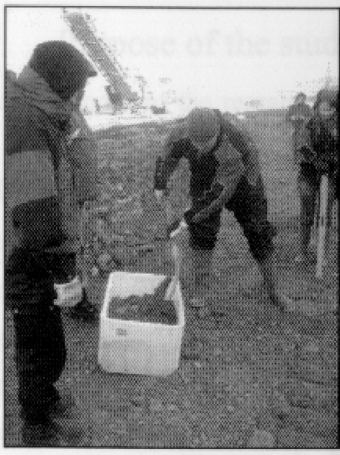

Figure 2: Collecting samples for seaving, crushing, pressing tests from the working face of surface miner.

Figure 3: Point load tests in the cutting face

Testing of limestone and oil shale cutting in surface mines

Recent tests have shown that decision for changing or improving extracting technology depends on usability of the equipment. Usability has been tested by measuring of technical production. The main factors influencing the production are- rock strength, cutting depth, and operator skills. Real productivity and effectiveness cannot be evaluated during short tests but already with real working conditions that depend on organizational conditions.

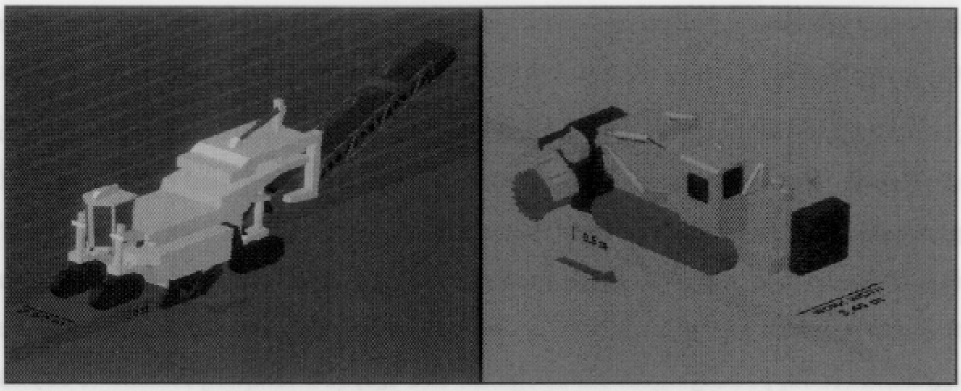

Figure 4: High selective surface mining with senter and rear orientated cutting drum

In spite of low depth of oil shale bedding the underground mining has spread instead of surface mining.

Development of oil shale underground continuous mining technology

Strategic aim of the development of oil shale underground continuous mining technology is development of mining technology in stratified conditions by testing continuous mining system in Estonian Oil Shale deposit. It improves coal mining possibilities due to enhancing cutting, supporting and face transport form high productive short-wall face (Fig. 5.). The main problems to solve are unstable roof, dilution of side rock and content of abrasive and hard parts of side rock inside or between usable seams.

Aim of the research is to introduce oil shale underground continuous mining technology on example of Estonian oil shale deposit in areas with arduous conditions. The results of in-situ testing can be used to improve existing situation in coal and oil-shale mining fields with complicated geological conditions and in densely populated regions.

The project stages include selective mining research for mining machinery development. In addition it results in increasing oil yield, decreasing CO2 pollution, decreasing ash amount, decreasing oil shale losses, avoiding vibration caused by blasting, avoiding ground surface subsidence (in case of longwall mining), increasing drifting and extracting productivity compared with current room and pillar mining, increasing safety of mining operations. The final aim of the research is to use BAT

(Best available Technology) for underground mining with arduous conditions of coal and oil-shale deposits.

The main problem to be solved is cutting selectively oil shale (15MPa) and hard limestone (up to 100MPa). The oil shale seam consists up to 50% of limestone layers and peaces. Other tasks are roof support at the face, stability of the main roof, roof bolting, selection of pillar parameters, backfilling with rock or residues (ash) from oil production, water stopping and pumping in problematic environment (30m3/t expected). Currently room and pillar mining with drill and blast technology is used. Supporting is done with bolts. Mining production is in total 14Mt/y, including 7Mt/y underground. Total raw material amount is 12Mt/y underground. Tests are made for opening two new mines, with total production 15Mt/y. Room dimensions in oil shale mines could be up to 15m in comparison with conventional coal mining with 5m dimensions.

The planned research project is based on the Sustainable Development Act and directs the development of the Estonian fuel and energy sector until year 2015. The document defines the current situation in the sector, presents issues set out in the EU accession treaty, prognoses developments in the energy consumption, states the strategic development objectives for the energy sector, the development principles and the extent of the necessary investments. The plan describes the problems that require further analysis and the functions of the state relating to supervision and regulation.

Estonia's oil-shale industry is at the beginning of introducing modern fully mechanized continuous miner systems, which will increase productivity and safety in the underground mines.

Previous experience of short wall continuous mining

A longitudinal cutting head type was first introduced in the former Soviet Union by modifying the Hungarian F2 road headers and in 1970s in Estonia by modifying the Russian coal road header 4PP-3. Evaluation of breakability was performed by a method developed by A. A. Skotchinsky Institute of Mining Engineering (St Petersburg, Russia). For this purpose over hundred tests were performed by cutting of oil shale and limestone. Evaluations were made for using coal-mining equipment for mining oil shale. Comparative evaluations were made by the experimental cutting of oil shale in both directions – along and across the bedding, including also mining scale experiments with cutting heads rotating round horizontal (transverse heads) and vertical axes (longitudinal heads). In both cases the efficiency was estimated by power requirement for cutting. The feasibility was shown of breaking oil shale by direction of cutting across the bedding by using cutting drums on horizontal axis of rotation. The research also evidenced that the existing coal shearers proved low endurance for mining oil shale. Therefore, the problem arose of developing special types of shearers for mining oil shale or modifying the existing coal shearers.

It was further stated that the better pick penetration of the longitudinal machines allows excavation of a harder strata and at higher rates with lower pick consumption for an equivalent sized transverse machine. It was reported that with the longitudinal cutting heads the dust forming per unit of time decreases due to smaller peripheral speed. The change in the magnitude of the resultant boom force reaction during a transition from arcing to lifting is relatively high for the transverse heads, depending on cutting head design. Specific energy for cutting across the bedding with longitudinal heads is 1.3–1.35 times lower which practically corresponds to the change of the factor of stratification.

The results of these tests were used in large body of fundamental research into rock and coal cutting in the UK during the 1970's and early 1980's at the UK Mining Research and Development Establishment.

Three decades ago a progressive mining method with continuous miner, which is most suitable for the case of high-strength limestone layers in oil-shale bed, did not exist in oil-shale mines of the former USSR and in Estonia. Therefore, up to now oil shale mining with blasting is used as a basic mining method in Estonia minefields while continuous miner was tested for drifting only. With regard to cutting, the installed power of coal shearers and continuous miners has increased since the original tests. Actual state of the market has changed and a range of powerful mining equipment from manufacturers like DOSCO, EIMCO, EICKHOFF, etc. is available now. Estonia has 30 years of experience in cutting with longwall shearers which were not capable of cutting hardest limestone layer inside of the seam. Tests with road headers have been carried out in 1970ties.

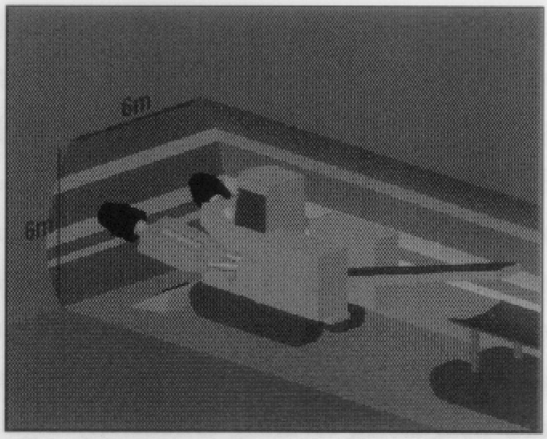

Figure 5: Double drum continuous miner for mechanical – selective room and pillar mining

Testing of surface strength of the oil shale and limestone layers inside of the seam, compressive strength and other figures is being worked out currently for both in surface and underground mines for operative evaluation of cutting possibilities and stability issues (Fig. 6.).

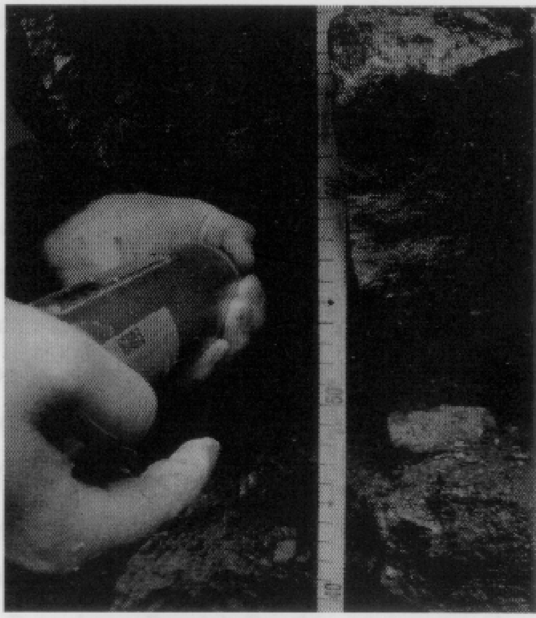

Figure 6: Testing surface strength of the oil shale layers inside of the seam, both in surface and underground mines

Backfilling

Previous experience from backfilling oil shale mines allows to assume, that there is possibility to use ash from powerplant, oil shale separation waste rock and/or limestone – as siderock, from selective mining for making bacfilling, selfhardening concrete as backfiling material for making artificial pillars in case of room-and-pillar mining (Fig. 7). This allows to decrease the size of current oil shale pillars and decrease amount of deposited ash in the ash deposit.

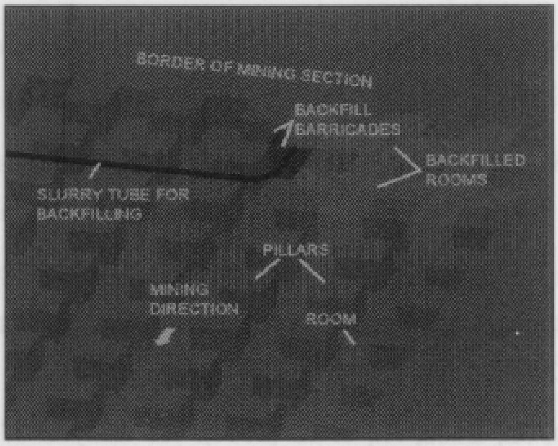

Figure 7: Backfilling of underground mines with concrete made from power plant ash and from waste rock aggregate

The question of using advanced technology is directly dependent on mining conditions that has to be suited together by criteria and successful tests.

Conclusions

The main reason of changing technology is increase of environmental tax for CO2, natural worsening of mining conditions and increase of oil price as side product for Estonian electricity production.

BAT analyse showed that one of the solutions for increasing oil shale quality is selective mining. Tests have showed that mechanical cutting is possible and the size distribution and increasing oil shale quality is possible.

In addition to better quality of the product that is related to the higher yield and less dilution, the opposition of the society decreases to mining industry due to its less impact to the surrounding.

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FUTURE OF OIL SHALE MINING TECHNOLOGY IN ESTONIA

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In the future, oil shale mining conditions will worsen and environmental taxes will be increased. Higher calorific value and more homogeneous material are required for more effective usage of boilers and generator units in power stations and oil plants. The solution for the mining industry is related to the optimal usage of mineral and technological resources, utilizing the best available techniques and modelling and visualization of mining impacts for explaining the changes in technology to the influenced parties. The main challenges for technologies in the future are related to the mining in environmentally or socially sensitive areas. One of the solutions could be utilizing selective mining and backfilling. Related tests have shown good results and show a promising future for sustainable oil shale mining.

Introduction

The modelling and planning of mining fields are based on measurements and analyses of the deposit which are gathered in parallel with industrial tests that provide initial data. For this purpose sampling tests of oil shale and limestone have been carried out from 2005 to 2007 in Estonia. The tests have been performed in *Väo Paas*, *Paekivitoodete tehas* and Aru Lõuna limestone quarries and Põhja Kiviõli, KNC Ubja and Narva oil shale surface mines and in Estonian underground mines. Similar previous tests have been executed in all Estonian oil shale mines. Backfilling and stability tests are in the planning stage for future implementation at underground mines.

Mining of non-traditional fuels in flat-laying deposits is well developed in Estonia, and the BAT (*Best Available Technology*) developed here could be used for future deposits elsewhere. Due to environmental restrictions, social pressure and deeper bedding of oil shale in potential mining fields, testing of high-productive, environmentally friendly mining is needed for

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successful continuation of an independent energy supply (oil shale) for Estonia [1]. New flexible and powerful mining technology will guarantee securing independence for the Estonian energy sector until the establishment of secure renewable energy production takes place.

Purpose of the study

The main purpose of the research is analysing the BAT and establishing criteria for selecting, planning and design of mining technology. The requirement for using a more effective extraction method is related to the worsening of mining conditions for oil shale and the increase in environmental taxes. Higher quality (calorific value, moisture, grain size) and courser material is required for more effective usage of boilers and generator units in power stations and oil plants [2]. The goals are

* to map possibilities for utilising BAT,
* to create criteria, methods, and bases for planning for choosing BAT for Estonian and similar mineral resources,
* to decrease the impact of mining on the environment,
* to improve mining environment, and
* to decrease the opposition of society to use of the minerals industry for the economy.

Additional goals include

* finding and selecting the criteria and bases for BAT,
* decreasing losses of minerals and
* lowering the impact on the environment from surface and underground oil shale mining. In general the objective is to optimize usage of mineral resources in the economy, and to establish sustainable development of mining, land usage, resource and subsurface usage.

Hypothesis

Coordinating criteria and methodology allows for decreasing expenses both in mining and planning. The experiences, gained in this field, can be used for other similar deposits elsewhere. It is possible to extract minerals in populated areas with suitable technology and at an acceptable cost. The criteria for solving the problems include minimum influence and cost, minimum influence to the environment and social sphere, minimum waste and residue production and maximum benefit for society, economy, education and country.

Methods

The main methods for the research include installation of sensors, gathering data and defining mining conditions, converting received data and using them for modelling. The methods also include testing of application, cooperation, range of usability and suitability of mine planning and software, laboratory and fieldworks for application of mining measurements equipment for modelling.

Analyses of Estonian energy systems have shown that increasing the fuel quality in power stations could improve the issues of high CO_2 emissions and at the same time increase effectiveness of power or oil generator units [2]. This goal can be achieved by decreasing CO_2, ash and water pollution. To avoid a potential problem of non-utilizable waste in stockpiles of mine areas, selective mining leaves the low-grade ore in mined-out underground or surface areas [3].

Selection of future technology

The selection of technology depends directly on economic considerations, but if economic issues are set aside, then BAT criteria have to be used (Fig. 1).

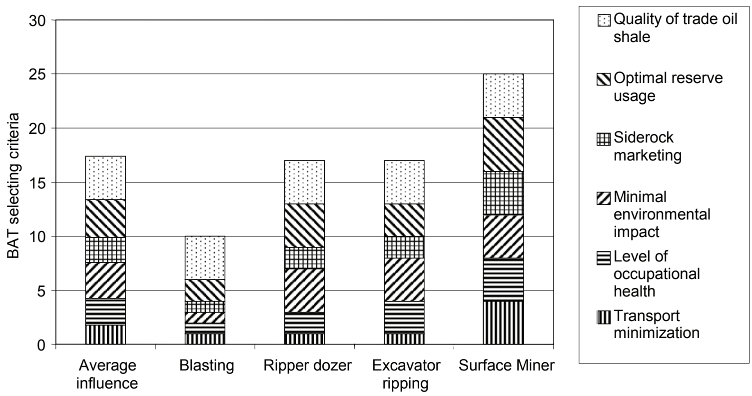

Fig. 1. Selecting mining technology for testing by BAT criteria.

Mechanical extracting

Given the condition of continually decreasing mining conditions, the main ways of increasing output material quality are selective mining (Fig. 1) or more effective processing after mining. The tests of mechanical mining have shown that selective mining with ripper-dozers have proved themselves, but in order to decrease losses, higher accuracy of cutting samples is needed [4]. This has been tested with high selective cutting with surface miners.

A surface miner breaks, crushes and loads material in one operation. The size of particles of the extracted rock depends on milling depth and operating speed. Usually it does not exceed 200 mm [5]. Two types of surface miners have been tested in Estonian mines, with centrally located and rear located cutting drum (Fig. 2 and Fig. 3).

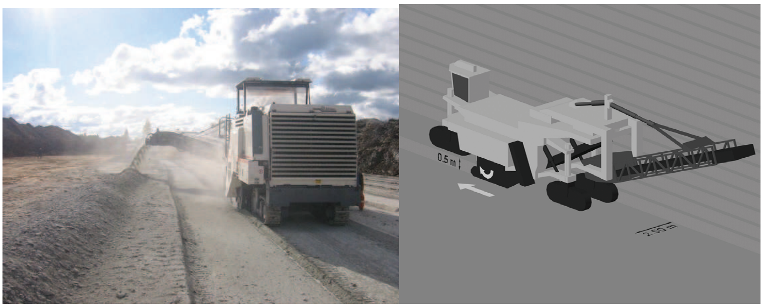

Fig. 2. High-selective surface mining with centrally located cutting drum.

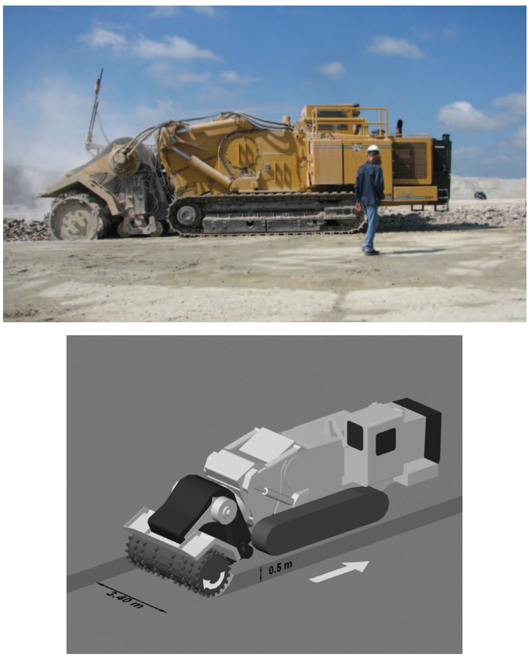

Fig. 3. High-selective surface mining with rear located cutting drum.

Testing of limestone and oil shale cutting in surface mines

Recent tests have shown that the decision for changing or improving extracting technology depends on usability of the equipment. Usability has been tested by measuring the production parameters. The main factors influencing production are: rock strength, cutting depth, and operator skills. Real productivity and effectiveness cannot be evaluated during short tests but with actual working conditions that depend on organizational conditions.

Mechanical cutting is accepted if the quality of the product and productivity of the machine is satisfactory. Generalized initial productivity chart of surface miner in various types of ore bodies shows a dependence on the material being mined and it mainly differs by resistivity to cutting, compressive strength and seam thickness (Fig. 4).

According to the tests, actual cutting time varies from 35 to 75% from total surface miners working time (Fig. 5) [6]. This percentage is highly

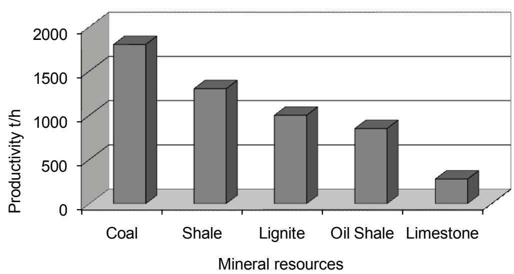

Fig. 4. Generalized initial productivity chart of surface miner, depending on cut material.

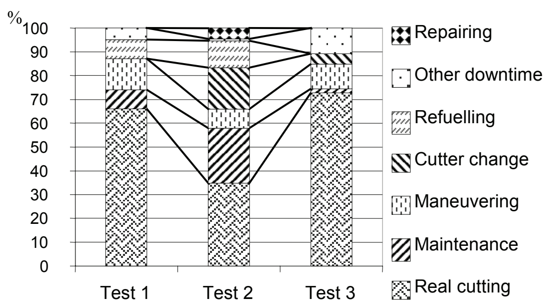

Fig. 5. Initial results of the surface milling tests in oil shale and limestone deposits.

dependent on organizational conditions, testing period and preparation and operational skills as well as suitability of the cutting drum and cutting tools.

As the result of initial tests – the minimum criteria for Estonian oil shale surface milling are: cutting depth 500 mm; machine weight 100 t; power 1000 hp; hard rock specific cutting tools and selectivity 5 cm.

Conventional underground mining

In spite of the shallow depth of oil shale bedding, underground mining has spread instead of surface mining. Currently room-and-pillar mining with drill and blast technology is used. Roof supporting is done with bolts. Total mining production is 14 Mt/y, including 7 Mt/y from underground mines. Total raw material production from underground mines is 12 Mt/y. Tests are made for opening two new mines, with total production up to 10 Mt/y. Room dimensions in oil shale mines could be up to 15 m in comparison with conventional coal mining with 5 m dimensions.

Development of oil shale underground continuous mining technology

The strategic aim of the development of oil shale underground continuous mining technology is to expand mining technology in stratified conditions by testing continuous mining systems in Estonian oil shale deposits [7]. This method improves coal mining possibilities due to enhancing cutting, supporting and face transport from high productive short-wall face. The main problems to solve are unstable roof, dilution of side rock and abrasive and hard parts of side rock inside or between usable seams.

The project stages include selective mining research for mining machinery development. In addition, it results in increasing oil yield, decreasing CO_2 pollution, decreasing ash amount, decreasing oil shale losses, avoiding vibration caused by blasting, avoiding ground surface subsidence (in the case of longwall mining), increasing drifting and extracting productivity compared with current room-and-pillar mining and increasing safety of mining operations. The final aim of the research is to use BAT for underground mining in difficult conditions of coal and oil-shale deposits.

The main problem to be solved is to selectively cut oil shale (15 MPa) and hard limestone (up to 100 MPa). The oil shale seam consists of up to 50% limestone layers and concretions. Other tasks are roof support at the face, stability of the main roof, roof bolting, selection of pillar parameters, backfilling with rock or residues (ash) from power plants or oil production, water stopping and pumping in problematic environment (30 m^3/t of produced oil shale expected).

The planned research project is based on the Sustainable Development Act and directs the development of the Estonian fuel and energy sector until the year 2015. This document defines the current situation in the sector, presents issues set out in the EU accession treaty, predicts developments in energy consumption, and states the strategic development objectives for the energy sector, the development principles and the extent of the necessary investments. The plan describes the problems that require further analysis and the functions of the state relating to supervision and regulation. Estonia's oil-shale industry is at the beginning of introducing modern mechanized continuous miner systems, which will increase productivity and safety in underground mines.

Previous experience of short-wall continuous mining

A longitudinal cutting head type was first introduced by Alo Adamson and Viktor Andrejev from the Estonian Branch of Skotchinsky Institute of Mining Engineering (Kohtla-Järve, Estonia) in the former Soviet Union, by modifying the Hungarian F2 road headers and in the 1970's in Estonia by modifying the Russian coal road header 4PP-3. Evaluation of breakability was performed by a method developed by Skotchinsky Institute of Mining Engineering (Moscow, Russia). For this purpose over a hundred tests were performed by cutting oil shale and limestone. Evaluations were made for using coal-mining equipment for mining oil shale. Comparative evaluations were made by the experimental cutting of oil shale in both directions – along and across the bedding, including also mining scale experiments with cutting heads rotating around horizontal (transverse heads) and vertical axes (longitudinal heads). In both cases the efficiency was estimated by measuring the power requirement for cutting. The feasibility of breaking oil shale by cutting across the bedding using cutting drums on the horizontal axis of rotation was shown. The research also showed that the existing coal shearers proved to have a low endurance for mining oil shale. Therefore, the problem arose of developing special types of shearers or modifying the existing coal shearers for mining oil shale [8].

It was further stated that the better pick penetration of the longitudinal machines allows excavation of harder strata and at higher rates with lower pick wear for an equivalent-sized transverse machine. It was reported that with the longitudinal cutting heads the formation of dust per unit of time decreases due to the lower peripheral speed. The change in the magnitude of the resultant boom force reaction during a transition from arcing to lifting is relatively high for the transverse heads, depending on cutting head design. Specific energy for cutting across the bedding with longitudinal heads is 1.3–1.35 times lower which practically corresponds to the difference in stratification factor.

The results of these tests were used in a large body of fundamental research into rock and coal cutting in Great Britain during the 1970's and early 1980's at the Great Britain Mining Research and Development Establishment.

Three decades ago a progressive mining method with continuous miner, which is most suitable for the case of high-strength limestone layers in oil-shale bed, did not exist in oil-shale mines of the former USSR and in Estonia. Therefore, up to now, oil shale mining with blasting has been used as a basic mining method in Estonia minefields while a continuous miner was tested for drifting only. With regard to cutting, the installed power of coal shearers and continuous miners has increased since the original tests. The market has changed and a range of powerful mining equipment from manufacturers like *DOSCO, EIMCO, EICKHOFF,* etc. is now available.

Estonia has 30 years of experience in cutting oil shale with longwall shearers which were not capable of cutting the hardest limestone layer inside of the seam. Currently mechanical short-wall mining is in the planning stage being in close relation with backfilling options (Fig. 6).

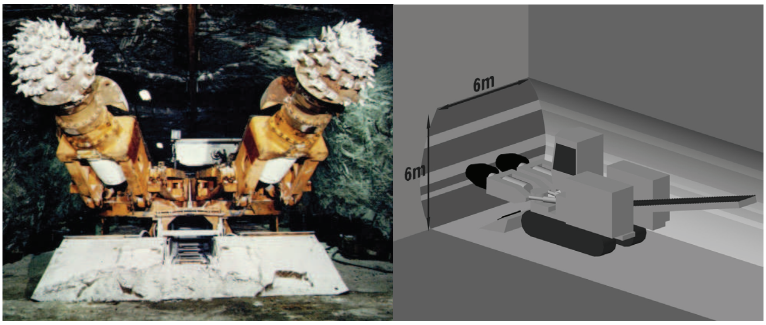

Fig. 6. Double-drum continuous miner for mechanical – selective room and pillar mining.

Backfilling

Previous experience with backfilling of oil shale mines and phosphorite mines allows one to consider that there is the possibility of using ash from powerplants, oil shale separation waste rock and/or limestone – as siderock from selective mining for perfoming backfilling [1, 9]. Selfhardening concrete could be used as a backfilling material for making artificial pillars in the case of room-and-pillar mining (Fig. 7). This allows for a decrease in the size of current oil shale pillars and an attendant decrease in the amount of deposited ash in the ash deposit.

The question of using advanced technology is directly dependent on mining conditions that have to be suited together by criteria and successful tests.

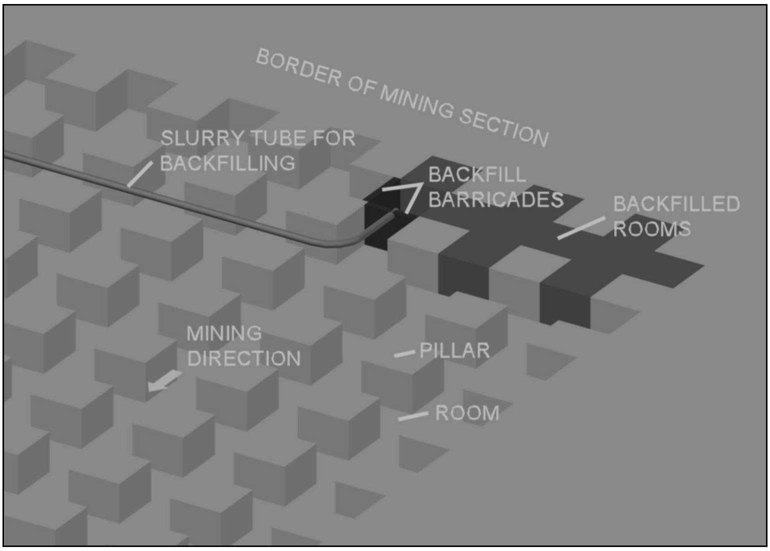

Fig. 7. Principal layout of backfilling in underground mines with concrete made from power plant ash and from waste rock aggregate.

Conclusions

The main reason for developing oil shale mining technology is to decrease CO_2 emissions from furnaces and to offset the continuing decline of mining conditions and increase of oil price as side product for Estonian electricity production. BAT analyses showed that one of the solutions for increasing oil shale quality (calorific value as well as grain distribution) is selective mining. Tests have shown that mechanical cutting is possible, and the size distribution and increasing oil shale quality are possible. In addition to better quality of the product that is related to the higher yield and less dilution, the opposition of society to the mining industry decreases due to its lower impact on the surroundings. The results of the test can be used for redistricting of mining regions and for creating criteria for resource usage and mining impact evaluation.

Acknowledgements

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QUALITY CONTROL OF OIL SHALE PRODUCTION IN ESTONIAN MINES

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The basic parameters of oil shale quality are heating value and grain-size composition. Heating value can vary considerably within the location in a deposit and depends on concretions and limestone content. Grain-size distribution and heating value depend directly on mining technology: breakage, transporting and processing. Energy distribution when using different technologies was determined. New boilers of oil shale power plants and oil retorts require a relatively constant quality of raw materials and fuel. The possibility of improving oil shale separation was investigated.

Introduction

Calorific value of oil shale has been discussed in many studies. The chances of obtaining a higher heating value have been examined. Previous studies have shown that quality management of oil shale production is mostly an economic problem [1].

The Estonia oil shale deposit is located in North-Eastern Estonia. The mineable oil shale bed consists of oil shale layers and limestone interlayers of various thicknesses. The basic quality parameters of oil shale are lower heat value as mined (Q^w) and grain-size range. Heating value and layer thickness fluctuate from place to place of the oil shale deposit. Heating value decreases by 0.07 MJ/kg per one kilometer in the lateral direction of the Estonia deposit. Heating value of oil shale layers can vary considerably within the location of the deposit and depends on concretions and limestone content [2].

Oil shale is used as fuel for electricity generation and shale oil production. For power generation, grain size of oil shale has to be 0–25 mm or 0–300 mm of lower heat value Q^w = 8.4–8.6 MJ/kg, depending on the mode of production. Grain size for oil production must be in the range 25–125 mm and lower heat value Q^w = 11.3–11.6 MJ/kg.

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The natural (geological) energy rate of a bed and layers has been determined in different systems by heating value in calorific bomb Q in kcal/kg. The lower heat value can be calculated as follows:

$$Q^w = (0.941 - 0.00941W)Q - 45 - 5.55W, \text{ kcal/kg}, \quad (1)$$

where W is moisture content, %.

Heating value as transferred into the modern system

$$Q^w \text{ (MJ/kg)} = 0.004186Q^w, \text{ kcal/kg}, \quad (2)$$

where Q^w is lower heat value.

Calorific value depends on oil shale layers and place where it is mined. At different parts of a mine different calorific value of oil shale can be determined. Therefore, enrichment and mixing of oil shale in concentration plant are needed.

Quality of an oil shale seam may deteriorate due to two factors – increasing share of limestone in layers and decreasing heating value of oil shale. This factors influence separation effectiveness. Firstly, decreasing oil shale share in run-of-mine (ROM, rock mass) reduces the yield of production. Secondly, decreasing heating value of oil shale will deteriorate the quality of fuel and oil.

Quality requirements for fuel raw material should be defined by both technical opportunities of extraction and consumption, and economic efficiency – the ratio of expenses for quality improvement to the effect received by using high-quality raw material [3].

The study was aimed at investigating the possibilities to increase calorific value of oil shale used for electricity generation and selecting a suitable equipment.

Methods

The main tool for analysis of the separation process is computational modelling with spreadsheet models and designing the process with CAD (equipment drawings and dimensions to fit them into existing concentration plant).

Oil shale separation process depends on grain size, heating value, moisture content, particle size distribution and secondary ingredients such as karst clay. Distribution of grain size and heating value depend directly on excavation technology.

In order to carry out the calculations for a mine field one has to know oil shale properties, geological and mining conditions, as well as those limiting the technical process. The main factor determining oil shale quality is its variable calorific value (heating value).

Great changes in oil shale heating value are explained by declining of oil shale seam from the center to the periphery of the deposit. For determination of average heating value in every oil shale layer with concretion (Q_l) the following formula is suggested:

$$Q_l = (Q_{os}\, m_{os} + Q_c\, m_c) / m_l, \tag{3}$$

where Q_{os} and Q_c are heating values (Table 1), m_{os} and m_c productivity of oil shale and concretions in mass. Mass productivity of the layer m_l

$$m_l = h_l\, d_l\,. \tag{4}$$

Geological testing can provide the data for m_l, Q_l and d_l, but for determination of the concretion amount the drilling data will be inaccurate.

On the basis of geological data, thickness of the oil shale layer without any concretion can be calculated by the formula:

$$h_{os} = h_l\, (d_l - Q_c\, d_c) / (d_l - d_c), \tag{5}$$

and total thickness and mass productivity of concretions in each layer are calculated

$$h_c = h_l - h_{os}, \tag{6}$$

$$m_c = m_l - m_{os}\,. \tag{7}$$

Basing on the data from Table 1, it is possible to compile the necessary mass and energy balances of run-off-mine oil shale (ROM) as material for separation.

Table 1. **Geological structure of oil shale and limestone and heating values for formulas (3)–(5) [4]**

Layers	Layer index	Heating values, Q_{os} and Q_c, MJ/kg	Volume density *d*, t/m^3
		Q_{os}	
Pure oil shale	F2	6.7	1.72
	F1	11.5	1.51
	E	17.5	1.28
	D	9.4	1.59
	C	14.2	1.38
	B	19.2	1.22
	A'	7.5	1.42
	A	15.1	1.37
Concretions	F, E, C, B	$Q_c = 2.9$	2.10
Kerogenic limestone	E/F, D/E, B/C, A/A'		
Pure limestone	C/D	0.6	2.45

Technology

For the computational modeling one has to know how oil shale bed is mined and also lumpiness of ROM.

Drilling-and-blasting and mechanical cutting methods demonstrate different properties of ROM. All beds (layers A-F2, excavating thickness 3.2 m) and mineable bed (layers A-F1, 2.8 m) are extracted by blasting. Average size distribution by cutting breakage: layers A, B+C, E+F selective cutting with surface miner Wirtgen SM2500 is shown in Fig. 1.

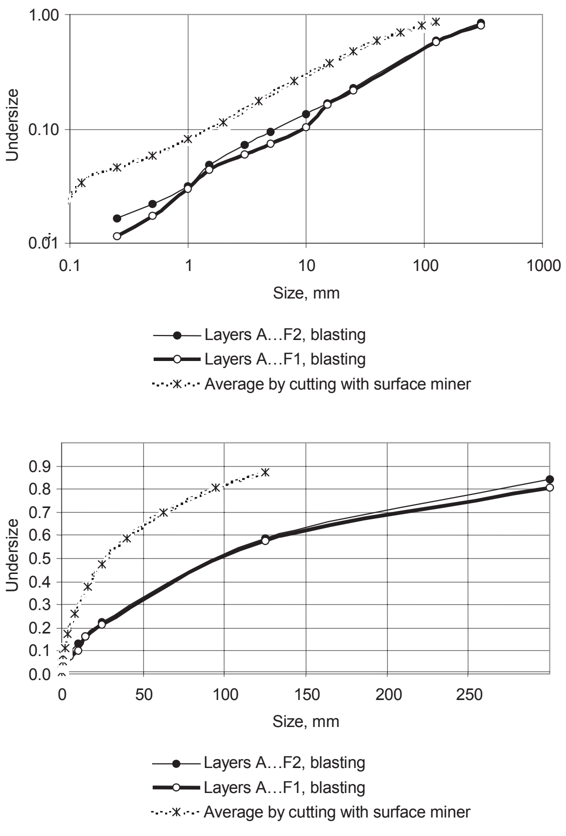


Fig. 1. Particle distribution in run-of-mine; upper – in logarithmic and lower – in normal scale.

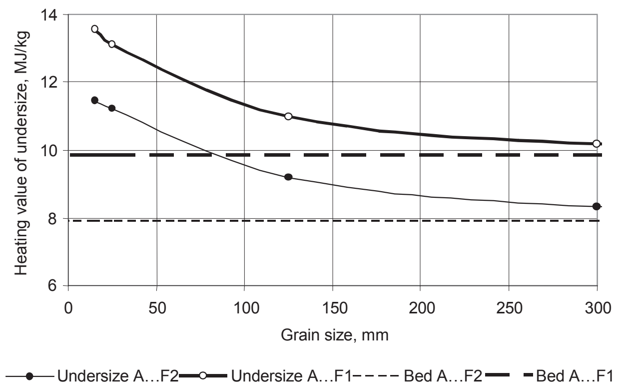
A-F1 – mineable bed, A-F2 – ROM diluted with unconditional layer F2

Grain-size distribution of ROM in the concentration plant can be described by the formula

$$y = A\,x^{n} + \delta, \qquad (8)$$

where: y – screen underflow; x – grain size, mm; A and n – parameters of distribution: A – "dustity", part of fine grain less 1 mm, n – granularity range; δ – pieces splitting at transport from the face to the factory.

For drilling-and-blasting method the share of not separated fine grains 0–25 mm makes 30–40% (Fig. 1), and heating value is 3–6 MJ/kg (layers A–F) higher than heating value of bulk ROM (Fig. 2, Table 2). If quality conditions of a commercial deposit are good, there is no need to use oil shale separation. But using this method about 5% (Fig. 2, Table 2) of fine grains <1 mm which include clay material will complicate the separation process.



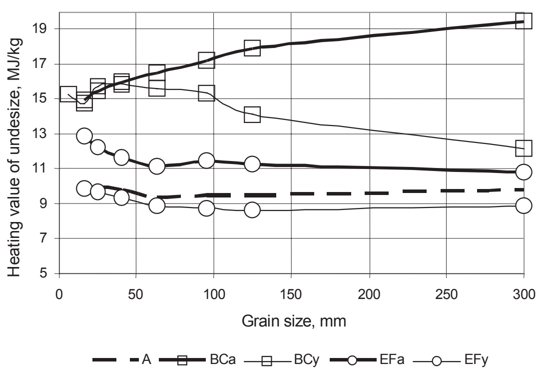


Fig. 2. Energy distribution of ROM: upper – blasting, lower – mechanic breakage with surface miner.

Energy distribution by blast breakage can be described by the formula

$$Q_x = \Delta Q \exp(-kx) + Q_{ROM}, \tag{9}$$

where: Q_x – heating value of the class 0–x (mm), ΔQ_x – effect of selective crushing, k – parameter of distribution, x – grain size, mm, and Q_{ROM} – heating value of ROM, weighed average of heating values of extracted layers and interlayers.

Table 2. **Parameters of grain-size and energy distribution in ROM for formulas (8) and (9)**

Distribution parameters	Symbol	Extraction method		
		Blasting	Cutting by surface miner	Ripping (after primary crushing)
Particle distribution				
Dustity, dust range	A	0.03–0.06	0.06–0.021	0.1–0.2
Granularity range	n	0.5–0.6	0.3–0.5	0.4
Pieces splitting at transportation from face to factory	δ	0.05–0.15	insignificant	
Energy distribution				
Effect of selective crushing, MJ/kg	ΔQ	3.0–5.8	0	No data, clearly 0
Distribution parameter	k	0.006–0.05	0	
Heating value of ROM	Q_{ROM}	Variable geological characteristic depended on site		

Separation equipment to achieve a higher quality

In the oil shale separation process different types of separation machinery are needed. These are screens, concentration tools, belt conveyors etc. To compose the layout of the machinery one has to know length, height and width of each unit. So we can decide how and where to place the equipment. Knowing the accurate production of material flows and collections one can draw a final layout for the separation plant.

Results

In the case of non-selective mining, oil shale has to be processed in a concentration plant to achieve the desired quality for customers. Oil shale is concentrated in heavy media separation drums.

The stages of the separation process of fine grains which could allow increasing heating value and reduce losses are presented in Fig. 3.

Separation process has multiple steps (a total of six stages). ROM is characterized by size $x \leq 300$ mm and heating value 5.85 MJ/kg. On the first stage of the separation process dry screening (Figs. 3, 4) separates the

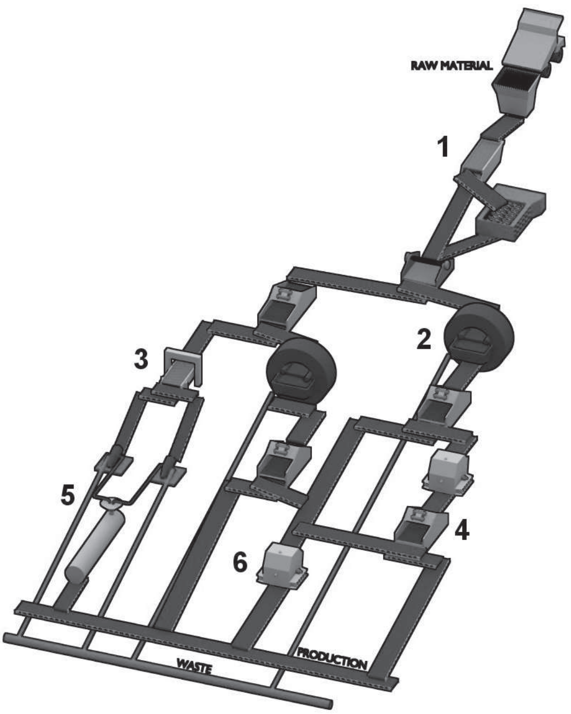


Fig. 3. Principal scheme of oil shale separation plant.

Oil shale separation processes includes: 1 – dry screening, 2 – coarse concentration, 3 – wet screening, 4 – fine concentrating, 5 – dewatering and 6 – production trimming.

material into fine grains 0–25 mm and coarse ones 25–300 mm. According to Eq. (8), fine grains ($x = 25$) make 37% of the total value with energy distribution 9.52 MJ/kg for dry matter and 7.42 MJ/kg for moisture (Fig. 4). Coarse particles ($x = 300$) make 63% and the energy is distributed equally 6.18 MJ/kg to dry matter and 4.98 MJ/kg moisture, respectively.

Further, fine grains 0–5 mm will be separated by wet screening and transported to dewatering for improving heating value. 2% of slime obtained in the process of fine concentration goes to dewatering. Coarse particles will be separated into 19% productive oil shale (11.51 MJ/kg) and 2% slime also going to the dewatering step. Waste from the coarse concentrate makes 41% with heating value 2.0 MJ/kg. The process yields 19% coarse concentrate (11.51 MJ/kg), 14% fine concentrate (11.43 MJ/kg) and 19% of extra fine and slime (8.42 MJ/kg), what makes totally 52% of oil shale with heating value 10.12 MJ/kg (Fig. 4).

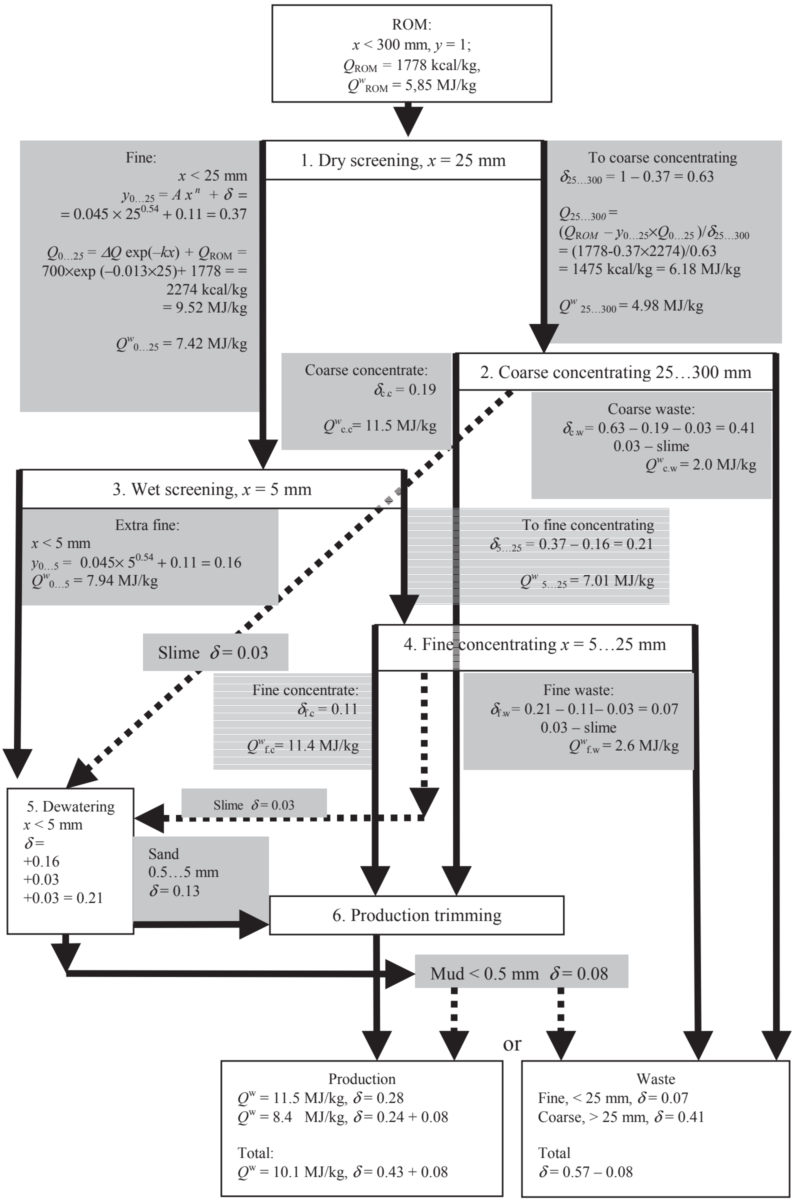


Fig. 4. Separation of oil shale fine grains.

The natural (geological) energy rate of the bed and layers has been measured by different systems basing on dry heating value *Q* in kcal/kg. Therefore heating value in kcal/kg is used.

The main problem of the oil shale separation process

Thanks to the feature of Estonian oil shale, the nature of accompanying limestone strongly differs from the properties of oil shale, and the raw material can be easily separated by gravitational methods. ROM is preliminarily selectively crushed, screened and transferred into the dense-media suspension. Part of the material will be sent after screening for separation of fine grains of high heating value [6]. The results of investigating enrichment of fine-grain oil shale in hydrocyclones, pneumatic separators and settling centrifuges demonstrate a principal possibility for increasing heating value of energetic oil shale [1]. Actual improvement of separation flow sheets and selection of suitable equipment can serve investigation of the oil shale concentration and transportation process from developments in mining to the storage of the finished product.

Discussion

To obtain a higher calorific value for oil shale as fuel we have to use selective mining in oil shale mining fields. In the case of underground mining it is complicated, but in surface mines it is applicable (selective extraction is technically supported by using mechanical cutting method). Using selective mining (using surface miner) in an open cast outlet of fine grains (0–25 mm) is approximately 50% (Fig. 2, line: average by cutting) with heating value of 11.8–12.5 MJ/kg. The best quality (high heating value of ROM) can be achieved if using selective extraction of the seam BC_a . With concretions of pyrite heating value of raw wet oil shale does not exceed 10 MJ/kg. Therefore in case of selecting only layers of limestone, the heating value of product will be 10 MJ/kg. For obtaining high-quality oil shale with heating value 11–12 MJ/kg it is necessary to realize selective cutting not only to separate limestone from oil shale layers, but oil shale has to be cleaned from concretions. To achieve heating value 11.5 MJ/kg, it is necessary to exclude cutting of layers A/B; B/C; C/D; D/E; F1 and selectively cut the upper part of the layer F2, where content of concretions makes up to 37%. Consequently, for 10.5 MJ/kg the layers A/B; C/D; D/E; F1 must be excluded.

During the process of an experimental test on a pilot filter press it was determined that the finest fraction of oil shale slime can be collected by pressure filtration so receiving a transportable sediment with dampness of 30%. Thus, for receiving a transportable technological sediment it is possible to use settling centrifuge and filter press which exclude slime emission to the slime pond. Investigations have shown that in the case of dewatering of slime by centrifuge it is possible to exclude about 60% of slime with particle size of 0.7–1.0 mm. At the same time, slime with dampness 25–30% will be transported together with the rest of unseparated material. The solids of the size of 0.01 mm represent 50%. Experimental testing of a hydrocyclone in the separation factory of the Estonia mine demonstrated the possibilities to separate the slime whose heating value is low, and add to the production about 1% of material with high heating value [7]. On the other hand, there is also the possibility to leave slime in the settling pond and extract it in the further process.

Prospects of extraction development in the Estonian oil shale basin are related to the modern-mechanized mining [5]. For example surface miners (SM) can find their natural application in projects where drilling and blasting is prohibited or where selective mining of mineral seams, partings and overburden is required. Surface miner can cut limestone and oil-shale seams separately and more exactly than rippers as the deviations are only about one centimeter [3].

Conclusions

The proposed calculation method allows selecting a suitable way for enhancing the heating value in oil shale processing using different mining technologies. The method is suitable for various parts of the Estonia deposit and offers the ability to solve problems in accordance with technical opportunities of extraction and separation processes. Quality control helps to carry out a correct selection of technological solution for future development of mining under various mining conditions.

Calculation model and visualization also helps to better prepare the new oil shale mines such as Ojamaa mine and Uus-Kiviõli mine.

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