Possibilities of gas utilization with special emphasis on small sanitary landfills

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Summary. Based on general observations on gas production in sanitary landfills, properties of some important landfill gases are discussed, especially with regard to the potential heat recovery. It has been shown, based on practice oriented considerations, that the utilization of landfill gases can be worthwhile even in small landfills. A scheme has been given which shows all the possibilities for collection, pretreatment, storage and combustion of the gases. The question of energy storage and energy utilization has also been addressed. The scheme has been discussed, as well as some of the processes, using the example of the hot water generation plant in the Croglio sanitary landfill in Tessin (Switzerland).

Calculation of the running costs shows that this plant, which is designed for a 335 MJ/h production, is working economically.

The term 'refuse management' implies the re-utilization of materials and/or energy. It is very seldom however, that one encounters good examples for such re-use, especially when dealing with small refuse disposal areas. Since even in small landfills (landfill volume up to

10^6 m^3 , refuse quantity up to 100 t/d), a considerable gas quantity can be produced, a pilot plant has been constructed¹ to study the possibility of utilizing the generated gas. The data thus obtained on gas utilization in a sanitary landfill serve as the basis of the following report.

Methane production

Knowledge of the production of methane, including that created in landfills, has been available for a long time. However, only recently, now that it has become clear that such gases can create safety hazards as well as problems in recultivation of the land^{2,3}, has one started paying much attention to its generation in landfills. In answer to the question why these problems have arisen only recently, there are any number of hypotheses. The following, however, seems to be most probable: In the past, refuse was buried by the communities in small, uncontrolled dumpings, which allowed aerobic decomposition. Today, we have large sanitary landfills, where the organic materials are mostly decomposed anaerobically.

Aerobic fermentation is caused by microorganisms which are also responsible for sludge digestion⁴. These organisms are able to convert part of the organic materials present in refuse into methane (table 1).

For a detailed summary of organic substances in refuse, refer to Stegman³.

Table 1. Waste composition⁵

Waste classification	Switzerland	Federal Republic of Germany
	1973 (%)	1971 (%)
Paper	36	22-25
Synthetics	4	2-3
Textiles, leather	8	2-4
Rubber, wood	20	10-20
Kitchen scrap		
Glass, gravel	12	10-16
Ceramics		
Metals	5-8	4-9
Miscellaneous	4-7	-

Table 2. Constituents so far found in landfill gases (from Winter⁷)

Constituents		
Methane	CH ₄	0-85% by vol.
Carbon dioxide	CO ₂	0-88% by vol.
Carbon monoxide	CO	2.8% by vol.
Ammonia	NH ₃	0-0.35 ppm
Hydrogen	H ₂	0-3.6% by vol.
Oxygen	O ₂	0-31.6% by vol.
Nitrogen	N ₂	0-82.5% by vol.
Hydrogen sulphide	H ₂ S	0-70 ppm
Ethylmercaptan	C ₂ H ₅ SH	0-120 ppm
Acetaldehyde	CH ₃ CHO	150 ppm
Acetone	C ₂ H ₆ CO	100 ppm
Benzene	C ₆ H ₆	0.08% by vol.
Argon	Ar	0.01% by vol.
Heptane	C ₇ H ₁₆	0.45% by vol.
Nonane	C ₉ H ₂₀	0.09% by vol.

Besides methane, a large amount of carbon dioxide is produced in landfills. Other gases are present only in small quantities (table 2).

With respect to the total attainable gas quantity, the information given in the literature varies from 60 to 290 m³ gas/t refuse³. From our own experience, a gas quantity of 100 m³ methane/t refuse can be expected to accumulate during 20 years.

Immediately after the deposit of refuse, a high production of CO₂ begins which reduces gradually in favor of methane production. The gas production varies greatly in quantity and composition during the first months. The primary unstable phase is followed by a second stable phase, where CH₄: CO₂ can reach a constant value of 3:2 (fig. 1).

Properties of some landfill gases and gas mixtures

It has already been mentioned that the gas mixture of landfill refuse consists mainly of methane and carbon dioxide. Relatively large amounts of nitrogen and oxygen are often present as well, especially in cases of forced suction, or in areas directly influenced by the atmosphere. Carbon monoxide and hydrogen, if they appear at all, are present at a low concentration (see also table 2).

Even in the stable phase the concentrations can vary, thus changing the ignition and combustion parameter. Table 3 shows the physical and chemical properties of the individual gases. The properties of the various gas mixtures are not yet well known.

Due to the high CH₄ content, the combustion parameter of methane itself is often used for the entire mixture. This yields on the one hand, an over-estimation of the energy properties of the concerned mixtures, and on the other hand, an under-estimation of the danger caused by the presence of a small quantity of CO and/or H₂. From the experiences with

Figure 1. Gas composition during decomposition of municipal refuse (from Farquar et al.⁶).

Table 3. Properties of some gases⁷⁻¹¹

Gas	Formula	Density (kg/m ³)	Net calorific value (kJ/m ³)	Critical temperature (°C)	Ignition range in air lower/upper (% by vol.)	Flame velocity (m/sec)	Minimum ignition energy (mJ)	Ignition temperature (°C)	Water solubility (g/l)	Common properties
Methane	CH ₄	0.717	35,600	-82.5	5/15	0.4	0.6-0.7	600	0.0645	Odorless, colorless, non poisonous
Carbon dioxide	CO ₂	1.977	31.1	31.1	—	—	—	—	1.688	Odorless, colorless, non poisonous at low concentrations ⁷
Oxygen	O ₂	1.429		-118.8	—	—	—	—	0.043	Odorless, colorless, non poisonous
Nitrogen	N ₂	1.250		-147.1	—	—	—	—	0.019	Odorless, colorless, non poisonous, non inflammable
Carbon monoxide	CO	1.250	12,640	-139	12.5/74	0.5	—	600	0.028	Odorless, colorless, poisonous, inflammable
Hydrogen	H ₂	0.090	10,760	-239.9	4/74	2.8	0.05	560	0.001	Odorless, colorless, non poisonous, inflammable
Hydrogen sulphide	H ₂ S	1.539		100.4	4.3/45.5				3.846	Colorless, poisonous
Air		1.29	—	—	—	—	—	—	—	Odorless, colorless, non poisonous, non inflammable

the Croglio sanitary landfill, where no considerable release of CO and H₂ was detected, the following statements can be made:

1. Under normal conditions, the flame of methane mixtures and air can reach a velocity of 0.4 m/sec. The combustion of the landfill gases released directly into the air yields a lower flame velocity (< 0.2 m/sec). This usually causes the flame to be unstable, leading to lifting and extinction.
2. While an ignition energy of 0.7 mJ is required for the methane and air mixture, a higher energy is necessary for the directly released gases from landfills. The gas ignition in the Croglio sanitary landfill has an electric arc of 15,000 V and 10 mA by an electrode gap of about 10 mm.

Problems with release of landfill gases

The gases produced through anaerobic refuse decomposition are easily ignited, and their combustion in absence of air can quickly set off an explosion. Control and preventive measures are therefore necessary in order to avoid this risk. Since the gases migrate underground, one should not under-estimate the danger for people and objects in the immediate vicinity. A strict management of the landfill is required to prevent such dangers. Through technical means, the leakage and underground movements of the gases can be reduced, controlled or eliminated. Specific safety measures are required for the landfill personnel in order to ensure safety in the working

areas. The gas mixtures of landfill contain a small amount of malodorous materials, which can be a nuisance to the personnel, as well as the residents in the neighborhood, if a leakage occurs. This unpleasant odor can be counteracted by the application of suitable chemical substances, or better yet, by careful coverage of the refuse with soil, and by collecting, processing or combusting of the gases.

Advantages of methane production from landfills

It is quite understandable that methane represents an important energy source. As we have seen from the above, 1 kg CH₄ is equivalent to 1.18 kg fuel oil, and 1 m³ CH₄ to 1 l fuel oil.

Assuming: a) that 1 kg refuse can generate about 100 l CH₄, b) that 40% of the produced methane can be recovered, whereas the rest is lost in the soil and atmosphere, and c) that each person produces on the average 0.75 kg refuse per day (this value has been calculated for the area of 'Consorzio eliminazione rifiuti del Luganese'), the potential methane production can be calculated to 75 l · person⁻¹ d⁻¹, of which about 30 l would be usable. The following figures illustrate the amount of methane, i.e., the fuel oil equivalence of the population of a small Swiss region (Lugano).

Population, approximately	100,000
Theoretical methane production	7500 m ³ /d
Recovery (40%)	3000 m ³ /d
Fuel oil, approximately	3000 l/d

The above shows, that even in such areas, it is worthwhile to consider the possibility of energy recovery from refuse landfill.

In the following discussion, some various means of gas recovery and utilization of communal refuse in organized landfills by anaerobic decomposition are examined.

The blockscheme in figure 2 shows the most important elements of a full-scale plant for gas recovery and utilization. It should be noticed that some elements are not absolutely necessary. The different elements separated by dashed lines, numbered 0-5, indicate the elements within the boundaries of the landfill.

The quality of landfill gases can be compared with that of pure methane. A landfill produces gas of optimal quality if the composition of the mixture has more than 60% of vol. CH_4 , and less than 50% of vol. CO_2 and 1% of vol. for the remaining gases. It is undesirable to have a high CO_2 content, and for N_2 or O_2 to be present; especially if the ratio $\text{O}_2:\text{N}_2$ is different from that of the atmosphere. In such cases, the atmospheric oxygen can diffuse into the landfill, causing the CH_4 to oxidize while the atmospheric nitrogen remains unchanged.

Recovery of gases

Water drains are often the means by which the gases

Figure 2. Possible elements of a landfill gas utilization plant.

tend to travel (fig. 2-I/a). This causes a release of unpleasant and easily flammable materials at the outlets. It is therefore advisable to use a siphon system to enable drawing of the gases without their being mixed too much with air. Experience from the Croglio sanitary landfill shows that atmospheric conditions can easily influence the composition of gases drawn. Since it is generally impossible to avoid a gas exchange between atmosphere and drainage system, the gases obtained have a large amount of nitrogen and oxygen. This means that the energy content of the gas mixture is very low. If a large amount of water flows through the drains, more CO_2 than CH_4 are dissolved (under normal conditions, about 1 l CO_2 /l H_2O and 0.01 l CH_4 /l H_2O). This causes the ratio CH_4 : CO_2 in mixed gases to change in favor of CH_4 . The drainage pits can eventually become potential explosion chambers and strict safety measures must therefore be taken.

The gases can also be sucked through ground probes (fig. 2-I/b) which are driven into the landfill. This allows a relatively inexpensive collection system. At the Croglio sanitary landfill, steel-tipped, 5-cm diameter ground probes were used, driven by a pneumatic hammer and reaching 5–10 m in depth.

From an area of about 1000 m^2 , about 40–60 m^3 CH_4 /d were extracted in 2 months time by using 10 ground probes. At the time of experiment, the landfill had been closed for 3 years.

The quality of the gases drawn off depends strongly on the air diffused into the landfill. This effect can be influenced by covering the landfill. The parameters for the gas suction as well as the distances between the individual probes should be determined separately for each landfill.

This system has the advantage that it can be installed immediately after completing the landfill, and without special preparations. Also, even if the collected gases seldom show outstanding qualities, gas mixtures of relatively constant composition can be easily combusted. This system is especially suitable where there is limited vegetation caused by high gas content in the upper layers of soil.

Gas recovery by way of a vertical stone-filled gas vent (fig. 2-I/c) is only effective if the upper part is well isolated from the atmosphere. If not, the gas quality is expected to be bad or the gas mixture can even be uncombustible. If there is not enough suction, the undesirable, malodorous gases can be an additional problem. To prevent possible water infiltration, this drainage should be connected to a water drain located above the soil layer. Already during the landfill operation, the gas vents should be filled with stones, which can disturb the truck traffic within the landfill. Since the gas vents must remain opened during this phase, they present a danger and are often a source of malodorous fumes.

Gas recovery from slanted combined drains (fig. 2-I/d) is possible when, during the filling phase of landfill, canals are built to let the water and gases travel through. These canals are easily built, are constructed in the form of a dry stone wall, and are slanted towards the surface of the landfill. These drains have the same properties as the gas vents. However, they can be more easily isolated from the atmosphere and disturb the landfill less during the filling phase.

Due to the fact that the landfill body is sinking while the surrounding ground stays stable, canals are often formed where gases travel easily to the surface. Such gas emissions can be accelerated by building a wall of stones or gravel (fig. 2-I/e). The extraction technology should proceed similar to the stone gas vent. The underground gas migration to the open should be controlled or reduced.

The gas recovery out of a landfill via a specially incorporated stone lens (fig. 2-I/f), can yield good results if this is located deep enough (beyond atmospheric influence), and if it can function as a collecting place for natural and man-made preferred flow channels (see also fig. 2-I/d). Seepage accumulation, however, should be avoided by, for example, connecting the base of the lens to a water drain or to a safe percolation zone. Experiences in the Croglio and other sanitary landfills confirm that the stone lenses will retain seepage if not drained. The recovered gases are generally of good quality as long as no air is sucked in through the drains.

Recovery with boring probes (fig. 2-I/g) is a relatively expensive system but gives the best results. Such borings are usually possible even after the completing of the landfill. The sucked gas is of a very good quality containing 95–99% of CH_4 and CO_2 . In order to prevent the gas quality from deteriorating by infiltrated air, the upper part of the bores must be isolated from the atmosphere with 1–3-m-thick layer of concrete surfacing or other similar materials. Even with such boreholes there is a danger that they will eventually fill with water so that they must be taken out of service. According to our experience, the diameter of the borehole is determined by the gas quantity to be drawn off. However, the costs of the borehole increase disproportionally to the diameter. It is therefore not economical for small and medium landfills to have a borehole more than 20 cm in diameter.

Pretreatment of gases

The recovered landfill gases, depending on their utilization must be pretreated to a greater or lesser extent.

The emanating landfill gases usually have a temperature of about 30 °C and a relative humidity of 100%. The cooling down of gases in the pipes causes water

condensation such that the deepest places fill with water. It is therefore necessary to separate water from the gases. How much needs to be taken out depends on how the gases will be utilized. A certain amount must be removed to prevent retention of water in measuring apparatus, pipes, ventilators, etc. The simplest water separation technique is to place a sufficiently large tank in the coolest area. These tanks should also have an emptying device, and are to be located at the lowest part of the pipes. When such tanks are filled additionally with fine gravel, they can function as a safety device against backfiring (fig. 2-II/a).

The CO_2 content must often be reduced in order to optimize combustion requirements or because the customers request it. One possible way of removing CO_2 is through the absorption by liquids, for an example, triethylamine (fig. 2-II/b). The CO_2 can be then released by heating up the liquid. The evaporated CO_2 can be reutilized in the event that this is economical. Unfortunately, such plants are only economical if an amount over $1000 \text{ m}^3 \text{ CH}_4/\text{h}$ is produced. They are thus unsuitable for small and medium landfills.

In some cases the separation of CO_2 is not sufficient, and other components (for example, C_nH_m) must be removed as well (fig. 2-II/c). In these cases, advance processes are needed (for example, by using a molecular sieve). Such a plant with an advance processing stage exists in Palos Verdes landfill near Los Angeles¹³. Also these plants are not economical for small and medium landfills.

The conversion of gaseous methane into liquid methanol (fig. 2-II/d) has significant advantages with regard to transportation and storage. Processes for chemical conversions have been known for a long time, but are not economical. Processes for biological conversions are presently being tested, and depending on the results produced, they could provide a good alternative in the future¹⁴.

Storage of gases

Since the gas production in a landfill is relatively constant and cannot be influenced within a short time, and since the energy utilization is nevertheless subject to changes, the following points must be considered: a) If gas production is higher than peak demand, intermediate storage is not required. During the remaining time, a considerable loss of gas is to be expected. b) If gas production is lower than peak demand, a possibility to store the gas must be foreseen, so that the gas supply can best be utilized. The different possibilities of gas storage are shown in the following paragraphs. In principle, only gas mixtures of good quality should be stored, whereby the oxygen content should be kept minimal for safety reasons.

Gasometers (fig. 2-III/a) are systems which have for a long time been known as digesters in sewage treatment plants. They consist of a container with a variable volume, in which the gas is stored almost without pressure. Such containers seem to be uneconomical for small landfills.

Compression containers (fig. 2-III/b) are unsuitable for storing landfill gases. This is due to the fact that the critical temperature of these gases is too low to be liquidized at room temperature ($T_k = -82.5^\circ\text{C}$ for methane). This is also true for propane and butane. If these gases are to be utilized as fuel, they should be stored in compression containers which can endure a pressure up to 200 bar. Compression containers can also be installed in small landfills if the gas quality is good, and if safety measures are taken.

The conversion of gaseous methane into liquid methanol would enable easier storage, since a normal liquid container could be used. Unfortunately, such conversion procedures are still in the development stage (fig. 2-III/d).

Combustion

The gas obtained from refuse landfill is usually burned in order to eliminate foul odors or to utilize it as an energy source.

In most cases, the heat produced by combustion of landfill gases is not utilized (fig. 2-IV/a). This type of energy waste is only reasonable if there are no consumers for the heat produced, and if the gas quantity is small or the gas quality is poor (a minimum heat equivalent of 125 MJ/h is required).

The easiest way to obtain energy from landfill refuse gases is by producing hot water of relatively low temperature ($< 130^\circ\text{C}$) (fig. 2-IV/b). The water must be pressurized so that a temperature above 100°C can be reached. If the hot water is not utilized in the area of production, this system is limited because large, well isolated pipes are required for transportation. Such an installation was built in the Croglio sanitary landfill and is working successfully (see fig. 4).

Combustion with production of super-heated water (fig. 2-IV/c) differs from the above in that the temperature of the water reaches 180°C . The advantage of this system lies in the fact that the produced heat can be transported more economically.

Combustion with steam generation (fig. 2-IV/d) is suitable for combustion of a large quantity of gases, and in cases where the heat has to be transported over a long distance (several km). Such a system works up to a pressure of 50 bar and a temperature up to 400°C . Among the 4 systems mentioned, this system is the most expensive and is not economical for small and medium landfills.

The combustion of digester gases has been in practice

Figure 4. Hot water supply plant system of Croglio's sanitary landfill.

for a long time. Such systems are often found in sewage treatment plants, but little is known about the application in landfills. This combustion of digester gases usually produces mechanical energy (fig. 2-IV/e), which can of course be transformed into electrical energy. The heat waste of the engines is also utilized in some cases. Examples are the 'Fiat Totem'-engine for smaller plants and the 'Caterpillar'-engine for larger plants.

Such a system is now realized in Palos Verdes, where a gas compressor is driven by a gas engine. In the landfill near Turin, a Fiat Totem-engine is utilized and in Croglio, a modified 'Renault'-engine has been recently experimented with. Since the sulfur content in a landfill's biogas is generally very low, in contrast to sewage treatment plants, desulfurization is not needed (table 2). The disadvantages of such a system, however, are the high initial and operational costs. It

should also be taken into consideration that constant adjustments of vaporizer and ignition are required, due to the changing concentration of the gases. This system is also applicable in small landfills.

Although the initial costs of gas turbines (fig. 2-IV/f) are high, the low operational costs and their durability enables a more economical system than the alternative engines. The disadvantage of gas turbines is the necessity of processing the gases in order to reach a minimum heating value of approximately 22,000 KJ/m³¹⁵. In addition, the efficiency of gas turbines is very low if the waste heat is not utilized, and the system can only be operated by specially trained personnel. Therefore, the use of turbines is only worth-while and economical for large landfills.

Heat storage systems

The hot water produced could be stored in order to optimize the utilization of the gases, or to minimize the boiler's dimension.

The simplest of heat storage systems makes use of good insulated water tanks (fig. 2-V/a). The water temperature depends on the recovery system (see 'Combustion section'). The large storage volume required is the main drawback. In Croglio, for example, 8000 l of water are stored with Δt of 70 °C. This corresponds to a heat amount of about 2500 MJ (equivalent to 60 kg fuel oil). Because of these drawbacks, this system is only economical for small and medium landfills.

To increase the storage capacity of the water tanks, special materials, such as naphtalin or mixtures of diphenyls, could be added (fig. 2-V/b). In this way, the heat capacity could be increased by a factor of 20 using the same volume. The costs, however, limit the usage of such heat storage systems to small and medium landfills only.

Utilization of energy

To utilize the energy, the following possibilities are conceivable: direct utilization of hot water or steam, as practised in the Croglio sanitary landfill (fig. 2-VI/a); usage of mechanical energy, as for example in Palos Verdes (fig. 2-VI/b); conversion to electrical energy, as it is often practised in sewage treatment plants (fig. 2-VI/c); operation of vehicles with compressed gas. (This possibility is limited practically to vehicles belonging to the plant facilities (see 'compression containers'). Processes for methanol production would greatly increase the advantages of such a

system (fig. 2-VI/d)); and utilization as raw material in industries (fig. 2-VI/e).

Standard of individual components of System I-VI

The blockscheme in figure 2 is divided into 6 sections representing various elements either inside or outside of the landfill. The dashed lines 0-6 indicate possible boundaries between each element. It is of course not possible to formulate rules which are always applicable, however, the following guidelines can be given:

- It is not recommended to combust landfill gases directly by using normal commercial means. This is because they are often unsuitable to be operated with such gases. In addition, most of the suppliers are not able to provide specially trained service personnel.

- If normal commercial means are nevertheless desired, the gases should be processed so that they have the same properties as conventional gases (for example, natural gas). These processes are only economical for landfills from which more than 1000 m³/h methane can be recovered.

- Since the concentration of individual components of gases are subject to wide variations, combustion problems can occur if alternative engines are operated.

- If landfill gases are to be transported, a careful removal of water is necessary since the condensation of the water in the pipes creates problems.

- There is no problem with direct transportation of heat, at least for small amounts (up to 0.2 Mcal/h) over short distances. For amounts larger than 0.2 Mcal/h and for longer distances, super-heated water or vapor should be used.

- Because of hygienic reasons, one should refrain from supplying gases directly to consumers.

In summary, it can be said that ideally the processes I-V (shown in blockscheme of paragraph 2) should be located directly in or near the landfill.

The hot water generation in the Croglio sanitary landfill

Using the above mentioned guidelines in Croglio, the utilization of energy is realized in the form of a hot water generation plant according to the following scheme.

The plant consists of 4 units, hot water generation, hot water storage, water distributor, and energy consumer; these are designed to enable further expansion.

Two boilers with a total production of 335 MJ/h are installed for the hot water generation. They are

Figure 3. Blockscheme of the Croglio sanitary landfill.

especially equipped with atmospheric burners for combustion of landfill gases. Each boiler has its own individual water cycle and feeds into the hot water tank.

The *hot water storage* consists of 2 isolated cylindrical tanks, which function according to thermal stratification, and are placed in series. The storage volume is 8 m³, and the temperature between 60 and 130 °C. The tanks are connected to a pressure equalizing tank.

Hot water distribution consists of fixed and flexible isolated pipes (heat transfer coefficient of polyurethane foam isolation at 20 °C: 0.084 kJ/mh °C)¹⁶, of hot water pumps and additional pressure regulators. The flexible pipes to the consumers are put under ground. A part of the hot water produced is used directly for the operation of the landfill heating and sanitary installations, while the rest is transported to private consumers. Heat exchangers are installed between the hot water cycle and the consumers for operational safety reasons. In order to ensure independence of consumers during disturbances, the heat exchangers are installed parallel to the existing heating plant. If the hot water supply cuts out, the heating plant of the consumer starts functioning automatically.

Costs

Based on the data obtained from the Croglio sanitary landfill, several cost aspects are given below to show

the amount of investment required for a plant which can function economically if hot water consumers are in the immediate vicinity.

<i>Investments (including salaries)</i>	
Burners and boilers (pipes 335 MJ/h)	SFr. 15,000.-
Hot water storage (2 tanks with a 3-m ³ content)	SFr. 11,000.-
Installations for heat transport (pipe lines, circulating pumps, valves, etc.)	SFr. 6,000.-
Underground pipes to the consumers (flexwell-pipes 30 m each way)	SFr. 10,000.-
Additional installations at the consumer (heat exchanger, boiler, electrical controls)	SFr. 15,500.-
Miscellaneous (costs for planning, etc.)	SFr. 7,500.-
Total investments	SFr. 65,000.-
<i>Revenues</i>	
Savings at the landfill operation itself by the conversion from electricity to landfill gas combustion for the production of hot water	SFr./y 8,000.-
Estimated energy supply to the consumers (introduction price)	SFr./y 1,570.-
Total revenues and savings respectively	SFr./y 9,570.-
<i>Amortization</i>	
Yearly amortization of 6% interest in 10 years	SFr./y 8,450.-

Experiences with the plant

The mentioned plant has been operating automatically since November 1979 without failures. The daily methane consumption is presently 150 m³, and the estimated efficiency is around 0.6.

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