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A Comparative Analysis of Energy and Water Consumption of Mined versus Synthetic Diamonds

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Abstract: In our research, we analyzed the energy and water consumption in diamond mining and laboratory synthesis operations. We used publicly available reports issued by two market leaders, DeBeers and ALROSA, to estimate water and energy use per carat of a rough diamond. The efficiency of the two most popular synthesis technologies for artificial diamonds—High-Pressure-High-Temperature (HPHT) and Microwave-assisted Chemical Vapor Deposition (M-CVD)—was examined. We found that the modern HPHT presses, with open cooling circuits, consume about 36 kWh/ct when producing gem-quality and average-sized (near-) colorless diamonds. ALROSA and DeBeers use about 96 kWh/ct and 150 kWh/ct, respectively, including all energy required to mine. Energy consumption of M-CVD processes can be different and depends on technological conditions. Our M-CVD machine is the least energy-efficient, requiring about 215 kWh/ct in the single-crystal regime, using 2.45-GHz magnetron for the support synthesis. The M-CVD methods of individual synthetic companies IIa Technology and Ekati Mine are different from our results and equal 77 and 143 kWh/ct, respectively. Water consumption for the HPHT and M-CVD methods was insignificant: approximately zero and 0.002 m^3/ct, respectively, and below 0.077 m^3/ct for ALROSA-mined diamonds. This study touches upon the impact of the diamond production methods used on the carbon footprint.

Keywords: energy efficiency; water intake; diamond mining; high-pressure; high-temperature; chemical vapor deposition; diamond synthesis; carbon footprint

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1. Introduction

Diamonds have many applications, and jewelry uses represent only a small portion of these. There has been an increase in demand [1] for diamonds in electronic and optical industries, owing to their physical advantages far surpass those of other materials. These advantages include thermal conductivity, a high refractive index, the highest degree of hardness, nitrogen vacancies in the crystal structure, and boron doping. Ref. [2] For these reasons, diamond is considered a promising material. However, the ecological impact of maintaining the supply of diamonds must be taken into account when considering the future use of diamonds. The ecological impact of diamond mining has been raised in mass media [3,4], with various players using different approaches to persuade potential clients—especially Generation-Z—that their diamonds (either mined or lab-grown) are more eco-friendly than those of their competitors. This study, therefore, focuses on the energy and water demands of the major diamond production methods, namely mining and lab-growing. We will begin with mining, the oldest method of diamond extraction, and then examine lab-growing technologies in depth.

The discovery of the vast kimberlite diamond fields in South Africa and Eastern Siberia played a pivotal role in the economic development of these macro-regions, and the effects persist to this day. Historically, generations of local people established communities near diamond factories, which then became outposts of industrialization. Diamond mining is a highly technological industry. Highly reputable think tanks have focused on the sustainable development of diamond mining, and ecology is of great importance to them. The extraction of diamonds requires the removal of vast amounts of rock, which is then washed in processing factories. These operations use a lot of energy (both electricity and gasoline) and water. Two sensitive environmental parameters–energy and water consumption per carat–are used as indicators of the general eco-efficiency of the diamond-mining process. One advantage of diamond mining is the relative openness of the major diamond producers, who readily co-operate with local communities or experts. Therefore, it was straightforward to collect the data required for this research by analyzing public reports of the major diamond companies.

Although each natural diamond field is unique, we will mainly use data from ALROSA, as they are one of the world's biggest producers of mined diamonds and boast a wide variety of deposits, including primary and alluvial deposits. Diamond distribution varies greatly from more than eight carats per ton of kimberlite in the "International" pipe to less than one carat per ton of sand in some alluvial deposits [5]. This makes ALROSA's data on the water and energy consumption per carat of a mined diamond highly relevant to our research, and we use it as a benchmark of the eco-impact of the diamond mining industry. Furthermore, we will compare ALROSA's data with another major diamond-mining company–DeBeers, which was mentioned in the work of Ali [6].

There is a cliché that lab-grown diamonds are inherently eco-friendly. In contrast, the Diamond Producers Association (DPA) claims that mined diamonds are responsible for "*69% less carbon emission per carat than laboratory-created diamonds*" [7]. Although if the M-CVD company will get the energy from water plants, the CO_2 footprint can be very low. To shed light on this dispute, we shall start from the basis–how diamonds are manufactured.

There are two main methods of lab-growing diamonds. In the HPHT (high-pressure, high-temperature) method [8], diamonds are formed in an iron-based carbon-rich melt (Fe-Co, Fe-Ni, etc.) under high pressure and high temperature. A hydraulic high-capacity press with six cylinders is used to create a pressure of 4–6 GPa inside a cubic chamber to accomplish this process. Iron is used as a base with other metals as additives (mainly cobalt and nickel), and a small diamond seed (or seeds) is provided as the prospective center(s) of crystallization. Graphite is used as a carbon source; it is heated up to 1500 °C and is essential to synthesis (Figure 1). Using a different number of seeds in the constant volume of the chamber controls the size of the diamond(s). In general, the more seeds (crystallization centers) there are, the smaller the size of the fabricated diamond(s) is, and vice versa–if one seed is used, only one diamond is grown, and its size is limited only by the carbon present in the iron-based melt.

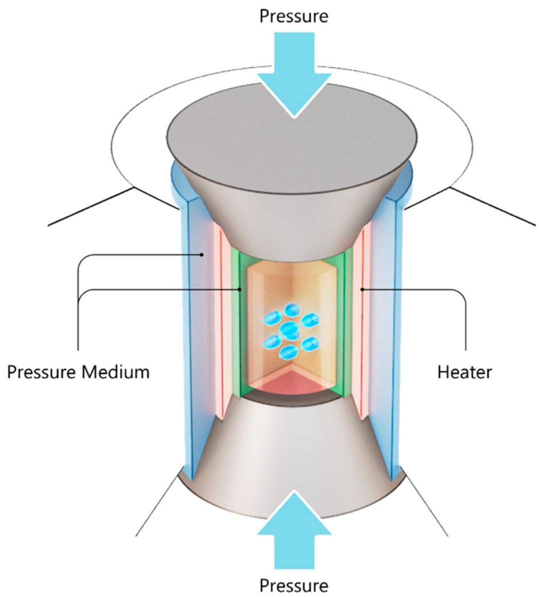

Figure 1. A HPHT belt-type chamber. The figure shows a few diamonds (blue) growing in an iron-based melt (orangish) inside a heated chamber under pressure.

The Chemical Vapor Deposition (CVD) method [9] allows one to obtain diamonds by depositing carbon on an initial diamond plate in a hydrogen-methane-based plasma. There are three main ways to create plasma in CVD reactors–hot filament [10], direct current [11], and microwave–referred to as HF-, DC-, and M-CVD [12,13]. Generally, M-CVD demands less electric power to grow single-crystal diamonds, and we have therefore used it in this study as a low-rate energy benchmark for all CVD sub-methods. To clarify, HF-CVD and DC-CVD use electricity to heat a wolfram filament and maintain a DC discharge between two molybdenum electrodes to create and maintain temperatures of up to 1000 °C, *a priori* requiring more energy to create plasma than the microwave method. Intuitively, comparing HF- and DC-CVD to M-CVD is similar to comparing an old-fashioned electric oven to a microwave–the difference in energy efficiency is striking, with the microwave being far more economical [14].

It should also be noted that there are other ways of producing synthetic diamonds, such as the explosive [15] and cavitation [16] methods, but these remain on the fringes of industrial production, and we do not have any viable data on them. Moreover, the diamonds produced by these methods are similar to abrasive powder in terms of size and quality. Therefore, these methods do not significantly influence the diamond industry.

There has not been adequate comparative analysis of the three major methods of diamond production, in the context of energy use and water consumption, mainly due to the rapid technological development of the industry. Furthermore, the authors have practical experience in all three diamond-production methods mentioned above–mining, HPHT, and M-CVD, so this paper is the quintessence of our competencies.

This study presents three different fabrication technologies (in Section 2), then analyzes and compares their combined energy use and water intake (in Section 3). Relevant mining data were sourced from the public reports of ALROSA and DeBeers, while lab-growing methods were analyzed based on experimental observations.

2. Materials and Methods

2.1. Mined Diamonds

Diamond mining (as all manners of mining) can be divided into three stages: exploring, mining, and processing. The last two stages are responsible for enormous resource consumption (gasoline, electricity, water, etc.).

Diamond mining is also a highly technological process and one intimately related to ecology. It is no wonder that the indicator of its ecological impact is one of the most important figures in annual reports of diamond mining companies. Our analysis of the energy and water consumption per carat of mined diamonds is based on the data sourced from ALROSA [17,18] and is presented in Table 1.

Table 1. The water and energy consumption of diamond mining over 7 years, for the ALROSA GROUP [17–19].

	2014	2015	2016	2017	2018	2019	2020	Actual/Average
Fresh water intake (m^3/ct)	0.676	0.642	0.543	0.199	0.077	0.115	0.125	0.340
Energy resources consumption, (kWh/ct)	92.78	89.72	95.83	90.83	97.78	98.61	108.69	96.32

Table 1 shows that the average energy consumption between 2014 and 2020 was 96 kWh/ct. Furthermore, there was an improvement in the water intake over these seven years: according to the report, water intake decreased by more than five times, from 0.676 m^3/ct to 0.125 m^3/ct (ALROSA Group). We will use the figures from 2018 as the most appropriate reference point for comparison with other diamond-production methods, as it is not foreseen that water intake will return to previous levels but will remain at the 2018 level of 0.077 m^3/ct.

The working paper of Ali [6] provides an energy usage value, taken from a DeBeers report, of 0.289 GJ/ct (80.28 kWh/ct), however, the values stated in the official DeBeers report are different (Table 2).

Table 2. Total energy use of DeBeers Group 2015–2018 [1] [20,21].

	2015	2016	2017	2018	Avg.
Direct and indirect energy use (MWh)	4.78	4.53	4.31	4.92	4.64
Energy from electricity purchased	24%	23%	28%	32%	27%
Energy from fossil fuels	76%	77%	72%	68%	73%
Diamond production (M ct)	28.8	27.4	33.4	35.3	31.2
Energy usage (kWh/ct)	166	165	129	139	150

[1] Data for 2019 and 2020 are not available.

The DeBeers average energy usage between 2015 and 2018 was about 150 kWh/ct, which is almost twice as high as the value stated by Ali [6].

We need to mention that we did not analyze the water intake of DeBeers. Our water consumption values for diamond mining are therefore estimated from ALROSA reporting alone.

Considering that more than half of the global mined-diamonds market is controlled by ALROSA and DeBeers (Table 3), we decided to focus on the data from these two companies. However, because there is a substantial gap between the energy usage values stated in the official reports of ALROSA and DeBeers (96 kWh/ct and 150 kWh/ct, respectively), we use these data separately, without averaging them. Moreover, it is important to mention that the climate of eastern Siberia (where the main ALROSA fields are) and that of southern Africa (the home territory of DeBeers) are very different. This is an additional factor against the averaging of data.

Table 3. Annual diamond production for 2015–2020 (Bain & Company [22,23]).

	2015	2016	2017	2018	2019	2020
Global (M ct)	127	126	151	147	139	111
ALROSA (M ct)	38.3	37.4	39.6	36.7	37.4	35.5
DeBeers (M ct)	28.8	27.4	33.4	35.3	31.3	27.2

2.2. HPHT Diamonds

The high-pressure high-temperature method is the most popular method of producing synthetic diamonds–since General Electric was the first company, who published this technology in the 1950s, ref. [24] the vast majority of all monocrystalline synthetic diamonds have been created in HPHT presses. For decades, HPHT diamonds were relatively small and suitable only for industrial purposes, such as abrasive powders. However, recently, as HPHT presses have allowed for a larger volume of iron-based melt and greater control, the paradigm has shifted. Nowadays, there is an influx of HPHT diamonds into the traditional-gem sector, and their prices are perceptibly lower than those of mined diamonds.

The idea behind the HPHT method is highly ecologically friendly–the method uses a relatively small volume of iron-based melt as the medium in which a diamond grows (Figure 1).

The energy use per carat for the HPHT method was estimated by considering a typical HPHT manufacturing facility equipped with one of the most widespread modern HPHT presses. It is referred to as an "850-press", it contains six hydraulic cylinders, each with a diameter of 850 mm. Figure 1 illustrates a chamber at the center of the press, in which the diamonds are grown. We have assumed a power rating of 3 kW for the cubic chamber for our calculation, which is the most common type.

At the beginning of the process, a pressure of 4–6 GPa is created by the inner 29.5-kW hydraulic oil pumps working for 10–15 min. During the growth process, the pumps are switched on approximately every 20 min, for 20–30 s, to maintain the pressure in the hydraulic system. The chamber must be heated to high temperatures while the diamonds are growing. The outside of the chamber must also be cooled to prevent the mechanism from overheating. This cooling is achieved with pump-driven water circulation and requires approximately 1 kWh.

Additionally, there are non-core energy demands related to lighting, staff needs, ventilation, etc., which should also be accounted for. These demands amount to approximately 1 kWh per press and include the short periods when the oil pumps are working, as mentioned above. Thus, growing diamonds in an 850-press chamber requires approximately 5 kW of electrical power; here, we calculate the estimated energy use per carat, based on growing ~40 ct over a 12-day cycle:

$$(3\ \text{kWh}^{\text{ to heat}} + 1\ \text{kWh}^{\text{ to cool}} + 1\ \text{kWh}^{\text{ non-core}}) * 24 * 12\ \text{days}/40\ \text{ct} = 36\ \text{kWh/ct}, \quad (1)$$

Therefore, the HPHT has a relatively low energy use of ~36 kWh/ct. Ali [6] reported the energy use of the American HPHT diamond producer Apollo Diamonds at 28 kWh/ct. This figure closely corresponds with our estimated value.

However, there are at least three factors that have a significant impact on HPHT energy efficiency–crystal size, nitrogen, and the type of cooling circuit.

Fundamentally, a larger crystal size requires a longer HPHT process. Hundreds of small-sized diamonds can be grown in the space of a few days, or a dozen larger ones can be grown over a few weeks. So, when one HPHT press is growing big-sized diamonds over one 12-day cycle, another press nearby can complete several cycles producing small-sized diamonds. The total mass of diamonds produced in each cycle is equal. Therefore, growing small-sized diamonds requires several times less energy than growing large ones.

However, there is little economic incentive to grow small-sized diamonds due to the direct correlation between a diamond's size and price. Growers aim to maximize the financial efficiency of the HPHT process rather than ecological efficiency. Moreover, finding a balance between the growing time and the final diamond value can be challenging. Small diamonds are cheap and simple to grow, and there is a relatively high demand for them from customers. Larger diamonds, around dozens of carats, are relatively complicated to produce, and there are few potential customers. Crucially, they constitute a greater risk as the complicated HPHT process must be controlled for weeks, not days. An experienced grower ought to be able to strike a balance between all the variables mentioned above. We used data for up to middle-sized in-demand diamonds for this study, with a growth time of ~12 days.

Nitrogen is an important factor in diamond fabrication; it can significantly enhance the performance of the HPHT process, although it makes diamonds non-colorless (from yellow to brown mainly), which generally sell at lower prices. Therefore, nitrogen can be seen as a "growth steroid" for diamonds, but most customers prefer colorless nitrogen-free diamonds. It should be added that there are two novel trends: one in the gem market, where there has been a new demand for fancy-colored stones, and another, in the quantum physics area, where there has been a demand for diamonds with nitrogen-vacancies-centers. However, this topic is beyond the scope of this paper. Here, we focus on the nitrogen-free HPHT process to obtain colorless and near-colorless diamonds classified as D-J by the Gemology Institute of America [25].

When focusing on diamond fabrication, one must not overlook the relative importance of the cooling circuit—if a closed circuit was used, chillers would be required, and energy use would double. China is undoubtedly the leader in HPHT diamonds, and the vast majority of Chinese HPHT growers use open circuits, which do not require complicated chilling systems. Instead, a common water reservoir is used to cool all the HPHT presses in a growing facility. Our analysis uses the Chinese method as the HPHT benchmark for an economic and ecological approach to growing diamonds. Manufacturers who use closed-circuit methods would consume approximately twice the amount of energy, significantly increasing the costs, which would bring them closer in this aspect to mining.

Taking the different types of cooling circuits for HPHT presses into consideration, it is impossible to predict water loss via evaporation from the surface of a technological water reservoir, as it is always open to the effects of sunshine and rain. To make it clear, there are about zero water losses in the case of closed-circuit HPHT cooling; and we assume that there is, on average, a zero balance in the open-circuit scheme. Moreover, unlike the M-CVD method, water is only used for cooling in the HPHT process and not as a source of hydrogen.

2.3. M-CVD Diamonds

In the M-CVD process, carbon is deposited layer by layer, allowing for excellent control of several of the crystal's parameters. This enables the creation of unique diamonds, either for the jewelry market or the quantum memory field [26]. The typical M-CVD reactor diagram is shown in Figure 2.

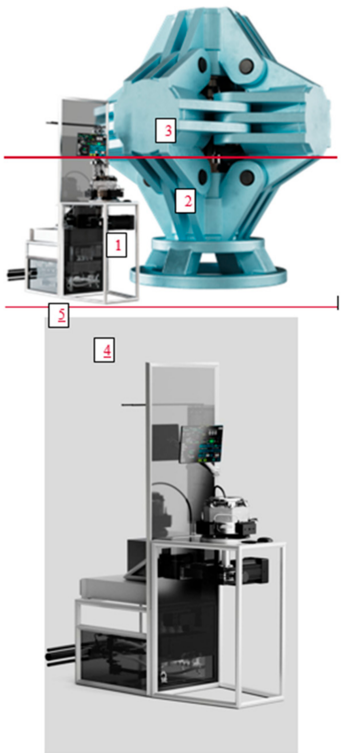

Figure 2. A diagram of 2.45 GHz MP CVD reactor. We can see a magnetron (1), a chamber (where diamonds grow, (2), control panel (3), pumps (4), electric, gas, and refringent supply cables (5).

Furthermore, on average, CVD reactors are more affordable than HPHT presses, making the method more attractive for start-ups and research teams. This process requires a source of plasma (for instance, a 6 kW 2.45 GHz magnetron), a source of hydrogen (a simple hydrogen station will suffice), and a source of carbon, of which methane (CH_4) is the most popular (Figures 3 and 4).

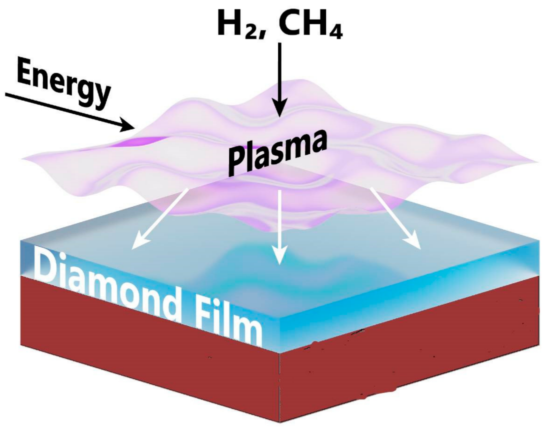

Figure 3. Diagram summarizing the M-CVD process: microwave-enhanced methane-hydrogen plasma covers a diamond film, which acts as the initial seed.

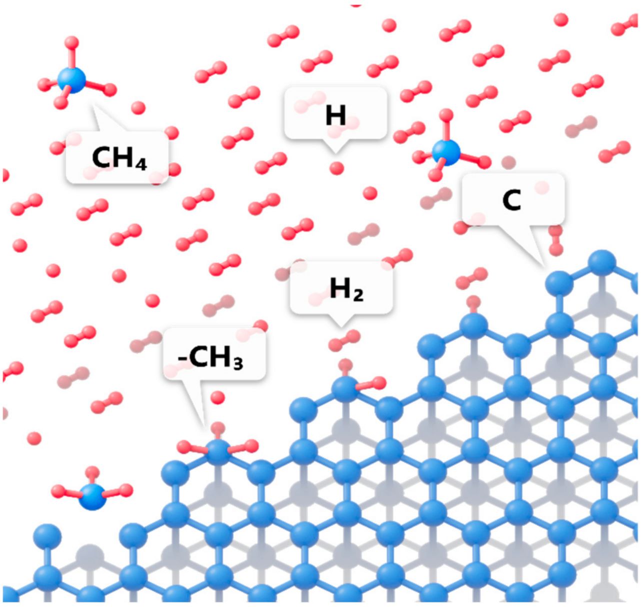

Figure 4. Diagram of M-CVD process: the dissipation of methane (CH_4) into methyl (-CH_3) and atomic hydrogen (H), the capture of a methyl group by the diamond cell, and further dehydrogenization.

However, the simplicity of the equipment does not necessarily mean a lower electricity cost, and more water is needed to produce hydrogen (about 2 L per carat or 0.002 m^3/ct).

An M-CVD reactor requires a source of plasma–the vast majority use magnetrons, while others (i.e., gyrotrons [14,27,28]) are less common. Magnetrons for M-CVD diamonds have a frequency of either 2.45 GHz or 915 MHz, and there is debate about which frequency is best for the M-CVD method. The 2.45-GHz M-CVD reactors are best suited for growing single crystals, as their plasma distribution "cover" is limited (diameter of about 100 mm) to the M-CVD deposit zone. The 915-MHz M-CVD reactor has a deposit area that is a few times larger, so many diamond seeds can be placed inside. This is probably the main advantage of the 915-MHz reactor, making it an "industrial" tool for growing many diamonds. However, the final obtained mass of diamonds depends not only on the initial number of seeds but also on the velocity of carbon deposition.

Although some researchers may use other carbon-based gases [29], the classic source of carbon (C) in CVD is methane (CH_4). Methane is the source of the carbon "building blocks," which are placed with the help of the atomic hydrogen inside the reaction zone. Many researchers have described the details of this process taking place in M-CVD [30–32]. In brief, the high temperature and microwaves enhance the disintegration of methane (CH_4) and hydrogen (H_2) into methyl radical (-CH_3) and atomic hydrogen (H). These reagents (methyl radical -CH_3 and atomic hydrogen H) are extremely unstable, and the main parts of them integrate quickly back into methane (CH_4) and hydrogen (H_2), but some of the methyl radicals are absorbed by the carbon cell of the diamond seeds. Therefore, the actual number of carbon "courier" (methyl radical -CH_3) and atomic hydrogen (H, which is essential to dehydrogenize methyl radical on the surface of diamond seed; the formula is $CH_3 + 3H = C + 3H_2$; Figure 4) depends to a large extent on the density (W/m^3) of plasma on a diamond seed. To make it clear, the higher concentration of electrons in a tiny volume right above the diamond's seed, the higher speed of deposition due to the higher number of methyl radicals and atomic hydrogen.

Unfortunately, our work does not consider the specifications of 915-MHz reactors, and our findings are for 2.45-GHz reactors only. Future work must consider the specific variables and values of energy usage for 915-MHz M-CVD reactors.

The second contributing factor to the energy consumption of CVD processes is product pureness, as lower nitrogen (N) levels in a diamond make for a more valuable product, both for gem and electronic applications. Although nitrogen is seen as an unwanted "brick," adding it speeds up the synthesis dramatically. It can significantly reduce energy use per carat. For instance, nitrogen can double the rate of diamond growth, producing twice the number of carats in the same amount of time. This, in turn, means that the energy cost per carat is halved.

However, while nitrogen is used to create nitrogen-vacancies in qubits and fancy colors in gem diamonds, it significantly reduces diamond quality quite. Even the price of a CVD reactor depends on its ability to protect the synthesis from nitrogen invasion.

Based on the details of magnetron frequency and unwanted nitrogen, we estimated the energy usage of the M-CVD method with a 2.45-GHz magnetron and a nitrogen-less diamond synthesis process. This is because nitrogen-less CVD diamonds are less energy-efficient, there is generally more demand for them.

Each M-CVD reactor also requires a hydrogen station and a cooler as essential support systems, so the total energy consumption is the sum of the energy consumed by the magnetron, the hydrogen station, and a cooler.

Our experimental results are based on a 6-kW, 2.45-GHz magnetron, which requires ~3.6 kWh on average (6 kW is the highest power rating and not required in the synthesis regime). The hydrogen station uses 1.0 kWh, and the water-based cooler is probably the most energy-inefficient part of the system, as it requires about 3.7 kWh to support water circulation and power cooler fans to prevent system overheating. The capacity of such an M-CVD reactor is about 30 ct of single-crystal diamonds per month. Non-core energy costs for lighting, computers, a kettle for the staff, etc., were estimated at 0.5 kWh per reactor.

It is notable that about half of the energy cost comes from the water-based cooler. While there are several ways of improving the energy usage of the cooling system, such as a different refrigerant or an open circuit, similar to the China-based HPHT arrays, such optimization is beyond the scope of this paper. Therefore, our estimate was for a water-based refrigeration system and will be different for an M-CVD operation that uses a different refrigerant or an open-circuit scheme. For example, the energy consumption of individual synthetic companies IIa Technology and Ekati Mine is different from our results and equal to 77 and 143 kWh/ct, respectively [33].

Energy use per carat for M-CVD was calculated as follows:

$$((3.6\ \text{kWh}^{\text{magnetron}} + 1.0\ \text{kWh}^{\text{H-station}} + 3.7\ \text{kWh}^{\text{chiller}} + 0.5\ \text{kWh}^{\text{non-core}}) \times 24 \times 30.5\ \text{days})/30\ \text{ct} = 214.72\ \text{kWh/ct} \quad (2)$$

In addition to the energy usage of 214.72 kWh/ct, the M-CVD method requires clean water to produce hydrogen–approximately 60 L per month, equating to 2 L per ct (0.002 m^3/ct).

In summary, energy use for M-CVD reactors could be reduced in the future through improved control of plasma density and better refrigeration systems for temperature regulation. However, electricity makes up a relatively low proportion of the current manufacturing cost of CVD diamonds (less than 10% of total costs), so there is no economic incentive to improve either the plasma distribution or cooling systems. The reasons are purely ecological.

3. Results and Discussion

3.1. Energy and Water Consumption

This paper focuses on diamond-producing methods in the context of energy usage and water intake. Table 4 summarizes all our findings.

Table 4. Respective average energy and water consumption per one carat of mined (ALROSA, DeBeers), and manufactured (HPHT and M-CVD) diamonds.

Origin of Diamonds	Energy Consumption (kWh/ct)	Water Intake (m^3/ct)
Mined	96 (ALROSA, public reports–2018)	0.077 (ALROSA, 2018)
	150 (DeBeers, public reports–2018	Not analyzed
HPHT ("850-press")	36	~0
HPHT (Apollo Diamonds)	(open water circuit, (near-) colorless, ~40 ct over, 12-day cycle) 28	~0
M-CVD (our)	215 (2.45 GHz, closed water-cooling, (near-) colorless, capacity 30 ct/month	0.002
M-CVD (IIa Tech)	77	
M-CVD (Ekati Mine)	143	Not analyzed

Table 4 shows the energy usage and water intake required per carat to obtain diamonds by three different methods–mining, HPHT, and 2.45-GHz M-CVD. The water intake of the world's second-largest diamond maker was not analyzed. Furthermore, the energy usage of lab-grown diamonds is highly dependent on the technical specifications mentioned in the table.

The HPHT method is generally more efficient in terms of energy use and water intake. Energy consumption of the popular lab-growth method, 2.45-GHz M-CVD, can significantly vary from 77 to 215, as you see in Table 4. Such differences can be explained by choosing some technological parameters, for example, cooling system, time synthesis, reactor capacity, etc. Our M-CVD process demands more energy per carat than both HPHT and mining, and it also requires clean water for synthesis.

Of the three methods, the mining conducted by ALROSA and DeBeers is second-most efficient in energy savings (see Table 4 or Figure 5)–mining operations of these companies are 2.3 and 1.4 times more efficient than our 2.45-GHz M-CVD method, though they require massive amounts of water (about 0.077 m^3/ct according to ALROSA reports), which is incomparably higher than all lab-growth processes. In M-CVD methods, it is possible to achieve energy efficiency similar to or even higher than mining using optimal technological conditions as confirmed by Ekati Mine and IIa Technology companies.

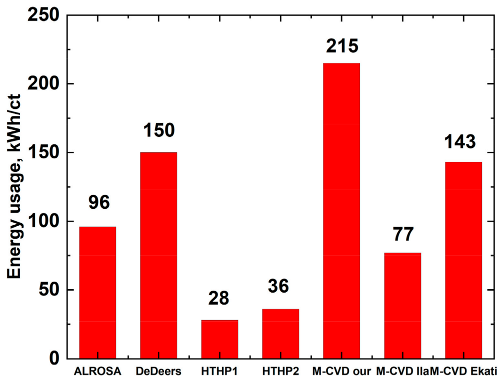

Figure 5. Bar chart showing the difference in energy usage between the investigated methods (HTHP1 refers to Apollo Diamond, HTHP2 refers to "850-press").

In addition, we have compared the number of various components required to start obtaining diamonds via the three methods (Table 5).

Table 5. Comparison of CAPEX, energy, and water required for different methods.

Method	Capital Expenditure	Energy Demand	Water Demand
Mining	**Very high** It is very costly to build a new concentrating factory with supporting infrastructure.	**Medium** (per carat) About 3/4-fossil fuels, 1/4-purchased electricity (according to DeBeers reports)	**High** Fresh water sources, industrial system of water-recycling.
HPHT	**Medium** Heavy-duty equipment, (68-ton hydraulic press)	**Low** (per carat) A peak load requires more than 30 kW per press at the beginning of a cycle, and about 5 kWh to support growing.	**Negligible** Open-circuit water cooling system for an array of presses (China, best-practice)
M-CVD	**Low** High-tech magnetron-based equipment, Expertise is a major contributor to the price.	**High** (per carat) Electricity 8.8 kWh–magnetron (2.45-GHz), chiller, hydrogen station. In addition, methane, as a source of carbon, has an insignificant contribution.	**Very low** Water as a source of hydrogen and as a cooling refrigerant.

Table 5 shows that each method has its advantages and disadvantages; however, the attractiveness of 2.45-GHz MP CVD technologies is based on economic reasons, not ecological. As mentioned above, chemical vapor deposition provides a rare opportunity for business people and researchers to synthesize diamonds without enormous capital expenditures. Furthermore, all lab-growing methods are flexible in terms of location–they do not need fresh water sources or significant industrial areas.

It should be mentioned that the use of methane as a source of carbon in CVD reactors creates additional risks due to its explosive nature. Although not directly related to energy or water consumption, this attribute of CVD must be noted. The usage of graphite as a carbon source in the HPHT process is safe, which is an additional plus of this technology.

Nevertheless, hydrogen is more dangerous the CH_4, because the molecule is light and small, therefore easily prone to leakage.

3.2. Recycling Water and Hazardous Acids

Even though diamond mining consumes much water, it does not contaminate the water used in the mining process. Diamond factories mostly use water to wash away clay and expose the diamonds–the vast majority of water-based stages do not involve any chemical reagents. Gold miners, by comparison, use cyanides to chemically extract gold from ore, while diamond miners never use cyanides. However, small amounts of strong acids are always applied in the chemical extraction of diamonds, in its final stage; after all, water-based processes have been carried out.

Furthermore, the vast majority of electricity consumed by ALROSA is created through Clean Energy–86% of it is generated in hydroelectric stations, including the Joint Stocks Company "Vilyuiskaya Hydro Power Plant-3" and "Hidrochicapa" S.A.R.L that is a part of the ALROSA Group in eastern Siberia (Yakutia) and southern Africa (Angola), respectively. This should be mentioned to emphasize the complexity of the ecological impacts of mining companies. However, we analyzed only direct energy usage, regardless of whether it is sourced from fossil fuels or hydroelectric stations (clean energy).

In addition, we did not analyze the use of acids in the three diamond processes, although acids are indeed essential for both HPHTand mining. Acids are sometimes used in CVD methods but in relatively smaller amounts. After CVD synthesis, acids or laser cutting are helpful in debilitating parasitic polycrystalline jackets (see Figure 6) that form on CVD diamonds. This constitutes a preparation stage for further operations.

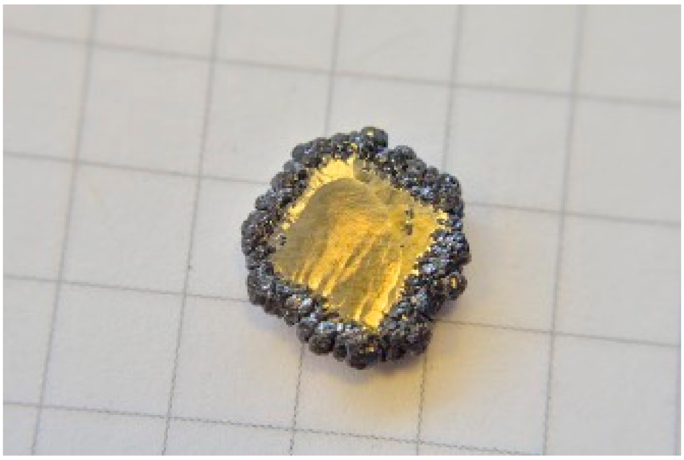

Figure 6. An M-CVD diamond with a polycrystalline jacket.

However, as mentioned above, strong acids in the final stages of all three methods do not significantly impact energy or water consumption.

3.3. Limitations

It is important to note that our energy and water consumption estimations for lab-growing technologies are based on many assumptions related to each described method's technical parameters. For instance, we assumed an open cooling circuit for the HPHT estimations, but if we changed this to a closed-cooling circuit, the figures would be closer to those provided by ALROSA. Moreover, if we added nitrogen to either the HPHT or CVD processes, the energy indicators would drop significantly. Moreover, only 2.45-GHz M-CVD reactors were investigated, which differ significantly from 915-MHz analogs. Therefore, we hope that our paper will be taken into account the authors' observations, not as a set of imperatives.

We consciously avoided the commercial aspects of diamond manufacturing, such as the price ratio between mined and lab-grown diamonds or the price divergence between a 300-kg M-CVD reactor and 68-ton modern HPHT 850 mm-press, the commercial aspect was beyond the scope of this paper.

4. Conclusions

This article summarizes our observations and clarifies some of the differences between mined and lab-grown diamonds. According to our estimations based on open-source data, using the HPHT method to fabricate medium-sized (near-) colorless diamonds, with the help of an open cooling circuit, is ~2.6 and ~4.2 times more energy efficient (36 kWh/ct) than mining and processing methods used by ALROSA (96 kWh/ct) and DeBeers (150 kWh/ct), respectively. Our M-CVD reactor, which uses a 2.45-GHz magnetron and water as a refrigerant, is 2.3 and 1.4 times less energy efficient than the figures reported by ALROSA and DeBeers, respectively (215 kWh/ct vs. 96 kWh/ct and 150 kWh/ct). However, this estimation only applies to single-crystal M-CVD synthesis and would be different for multi-growths or polycrystalline synthesis. Also, energy consumption will depend on the type of machine used and the conditions chosen. M-CVD method of individual synthetic company IIa Technology is 1.3 and 2.0 times more energy-efficient than the figures reported by ALROSA and DeBeers, respectively (77 kWh/ct vs. 96 kWh/ct and 150 kWh/ct). M-CVD method of Ekati Mine company is 1.5 times less energy efficient than ALROSA (143 kWh/ct vs. 96 kWh/ct) and is 1.05 times more energy efficient than reported by DeBeers (143 kWh/ct vs. 150 kWh/ct).

The HPHT and CVD methods are essentially water-less (0 and 0.002 m3/ct, respectively), with mined diamonds being responsible for greater resource consumption: slightly less than 0.077 m3/ct according to the ALROSA report of 2018.

We cannot say that all lab-grown diamonds should be inherently preferable over mined ones because energy and water consumption are different for various deposits and climates conditions. Furthermore, the described 2.45-GHz M-CVD method is less energy-efficient than mining operations. It is undeniable that all lab-grown diamonds are more water-friendly than mined ones, although, according to ALROSA reports, there is a positive dynamic in mining toward reducing water intake per carat.

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