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Archetype Modeling of Mining Method Subcategories for LCI in Canadian Mines

Overview of Mining Method Categories in Canada

In Canada's mining sector, **two primary mining methods** dominate: **open-pit (surface) mining** and **underground mining** [1]. Open-pit (or open-cast) mines involve removing large amounts of overlying rock and soil to excavate minerals from a broad, near-surface deposit – essentially creating a large hole or pit at the surface. Underground mines, in contrast, access deeper ore bodies via shafts or ramps and a network of tunnels beneath the surface [1]. A few operations may also use specialized methods like **placer mining** (for alluvial gold or diamonds in river gravels) or **solution mining** (in-situ leaching, used for some minerals like potash), but for **metals in Canada the vast majority of active mines are either open-pit or underground**.

Subcategories (Variants) of Mining Methods: Within these broad methods, there are important subcategories that describe how the mining is carried out:

- **Surface Mining Subcategories:** The typical technique for Canadian metal mines is open-pit with **truck-and-shovel** excavation. (Other surface methods like strip mining or mountaintop removal are more common in coal or other contexts, and dredging/placer methods are mostly limited to placer gold or diamond deposits.) Essentially, most "open-pit" metal mines in Canada use large shovels or loaders to dig ore and waste, and haul trucks to transport material. Thus, we can consider all these as variations of the open-pit category for LCI purposes. Differences in equipment (e.g. dragline vs. truck-and-shovel) could exist at some mines, but in Canada's metal mines truck-and-shovel is standard for open pits.

- **Underground Mining Subcategories:** There is a wider variety of underground mining methods, often chosen based on deposit geometry, ore strength, and other factors. Key underground subcategories include:

- **Caving Methods:** These are **high-volume, low-cost** methods where the ore and surrounding rock are allowed to **cave (collapse) under gravity** in a controlled way. Examples are **block caving** and **sublevel caving**. Caving methods eliminate much of the drilling and blasting effort (in block caving, an undercut is created and then the ore body progressively collapses under its own weight) and **do not require backfilling** the mined void [2]. Because of this, caving methods achieve very high production rates and are considered the **most productive and lowest unit-cost** among underground methods [2] [3]. They are typically used for large, low-grade deposits at depth (often the kind that might otherwise be mined by open pit if near surface).
- **Open Stoping Methods:** These involve mining out ore in sections (stopes) while leaving some support (either pillars of rock or installing artificial supports). Variants include **long-hole open stoping**, **room-and-pillar mining**, **shrinkage stoping**, and others. These methods usually require **partial backfilling** of mined voids for stability after extraction, except in cases like room-and-pillar

where pillars are left unmined for support. They are common in many Canadian underground mines (especially for hard-rock gold, nickel, copper mines, etc.), where miners drill and blast the ore and remove it, often using gravity or machinery to collect broken ore. Compared to caving, stoping methods are **more selective** – they can target higher-grade sections – but typically have **lower throughput** and may need extra steps like backfilling or leaving pillars which add to operational effort.

- **Cut-and-Fill Stoping:** This is a special case of stoping that is very selective. Ore is mined in horizontal slices, and after each slice, the void is **completely backfilled (usually with a mix of tailings, waste rock, and cement)** before mining the next slice above. Cut-and-fill is used for irregular or narrow, high-grade veins where maximum selectivity is needed. It has a **high cost and energy use per tonne** because of the continuous backfilling and stop-start nature, but it maximizes ore recovery and ground support.
- *(Note:* Other methods like longwall mining are primarily for flat-lying deposits (e.g. coal) and not common in metal mining, so they can be ignored for Canadian metal mines.)

In practice, many **mines use a combination** of methods. For example, a mine might start as an open-pit and then transition to underground (common for deposits that extend deep). Or an underground operation might use different methods in different zones (e.g. a mine could use long-hole stoping in one area and cut-and-fill in another, depending on ore geometry). The **MiningDataOnline** information you extracted likely lists multiple techniques for a single mine (e.g. *"Truck & Shovel; Longhole stoping; Drift-and-fill"* for a mine that has an open-pit and various underground sections [4]). For LCI modeling, you'll need to **group these detailed labels into broader categories**. A sensible grouping for all active Canadian mines might be: - **Open-Pit Surface Mining** (including all truck-and-shovel open pits, quarries, etc.), - **Underground – Caving** (if any mines are explicitly using block caving or sublevel caving), - **Underground – Non-Caving** (conventional stoping methods, with or without backfill), - **Placer/Other** (if applicable, e.g. alluvial gold operations, though these might be few in your dataset).

This grouping recognizes the major differences without over-complicating the categories. Now let's examine whether these subcategories have **meaningfully different life-cycle consumption patterns**.

Differences in Energy and Material Consumption Patterns (LCI) by Method

Broad Distinctions (Open-Pit vs Underground): The largest contrast in operational resource consumption is between surface and underground mining. Open-pit mines typically handle **huge volumes of material** – not only ore but also waste rock (overburden and low-grade material) that must be stripped and moved to access the ore. This results in **high diesel fuel use** for excavation and haulage equipment, and a high "strip ratio" (tons of waste per ton of ore). By comparison, underground mines access ore more selectively (less waste rock removal), which can reduce the total tonnage moved. Consequently, open-pit operations tend to be **more energy-intensive per unit of mineral produced** than underground mines of the same commodity [5]. In fact, an analysis by CEEC (2018) of global copper mines found that **open-pit copper mines consumed roughly ~26 GJ/tonne of copper** produced, versus about **16 GJ/tonne for underground copper mines**, on average [6]. The higher energy intensity for open pits is largely because they often exploit lower-grade deposits, so they move and process much more rock to get the same amount of metal [5].

The **energy mix** also differs: open-pit mining is overwhelmingly powered by **diesel fuel** (for loaders, shovels, haul trucks, etc.), with relatively modest electricity needs (lighting, some drilling, pumping). In typical open-pit mine sites, about *60%* of total site energy might be consumed in the mining operations (mostly diesel) and ~40% in mineral processing [7]. By contrast, **underground mines** rely heavily on **electricity** for ventilation fans, hoisting systems (elevators or skips for ore), underground lighting, and drilling equipment. A life-cycle study noted that in a typical underground mine about 40% of the mining-stage energy is electricity (primarily for ventilation) and 60% diesel (for underground loaders, trucks, etc.) [8]. Underground operations also tend to use **additional materials**: for example, ground support (rock bolts, shotcrete) and backfill material, which entail energy for production and transport (and contribute to the LCI in terms of material inputs). Overall, though, the **diesel-intensive nature of open pits** (with large haulage requirements) often makes them **emit more GHGs and use more energy per tonne** than underground mines for the same commodity output [5].

Differences Among Underground Mining Subcategories: Even within underground mining, the choice of method can lead to different consumption patterns in the life cycle inventory:

- **Caving vs. Stoping Methods:** As noted above, caving methods (block caving, sublevel caving) are highly productive and **don't require backfilling** the void. This has two implications for LCI: (1) **No backfill operations** means significant savings in material and energy – there is no need to mix and pump cemented tailings or waste rock to fill voids after mining, an activity which in other methods consumes power and cement. (2) Caving methods also can reduce drilling and blasting needs – e.g. block caving largely relies on the rock breaking under gravity after initial undercutting [9] – which means **less explosive consumption** and potentially lower energy for rock-breaking. These factors make caving methods **more energy-efficient per tonne of ore** compared to more selective stoping methods. An underground mining report by an investment firm explicitly states that *"sublevel caving … is less energy intensive than open pits (where large quantities of waste must be moved) and [also less energy intensive than] non-caving underground methods which require backfill"* [3]. In other words, a caving underground mine can approach the scale-efficiency of an open pit (high tonnage, low unit costs) but without the huge waste stripping, giving it a potential energy advantage in LCI terms.

- **Stoping with Backfill (e.g. Cut-and-Fill, Long-Hole Stopes with backfill):** These methods incur extra material and energy overhead. **Backfilling** uses a mix of water, crushed waste (or tailings), and often cement binder to refill mined-out voids for stability. This process requires running mills or mixers to prepare fill, pumping the heavy slurry underground, and the production of cement – all of which add to the **indirect energy and carbon footprint** of the mine. A recent life-cycle assessment study comparing Chinese underground iron mines found that **mines using backfill methods had higher energy consumption and carbon emissions than caving-based mines**, largely due to the energy for **mixing/pumping fill and the production of cement binder** [10] [11]. For example, when comparing 30 case studies, the average life-cycle energy consumption for **backfilling-based mines was about 710 GJ per kiloton of ore**, versus **approximately 674 GJ/kt for caving-based mines** (about 5% lower) [12]. This gap widened when focusing only on operational electricity and diesel (excluding explosive energy): caving-based mines used significantly less electricity on average (because they avoid running backfilling equipment and have simpler material-handling) – around **39 GJ/kt in electricity for caving vs 57 GJ/kt for backfill methods** – resulting in **overall energy consumption ~18% lower** in caving mines than in backfill mines on a per-ton basis when considering fuel and power use [13]. Additionally, cement added substantially to the **carbon footprint** of backfilled mines, contributing CO_2 from its production; in those case studies the backfill mines had much higher CO_2 emissions per ton of ore than caving mines (often 3–4 times higher CO_2/ton, primarily due to cement and greater power use) [14] [10]. This illustrates that **backfill-heavy methods are more energy and carbon intensive**, while caving methods are "cleaner" in an LCI sense for the same ore throughput [15].

- **Other Underground Variations:** Even among non-caving, non-backfilled stoping methods, there can be differences. For instance, **room-and-pillar** mining leaves pillars in place and typically doesn't use as much backfill (often none until final stage pillar recovery, if done). This could make its material usage lower than a cut-and-fill mine. However, room-and-pillar is usually used for relatively flat, shallow deposits (more common in coal or evaporite mining; not very common for Canadian hard-rock metal mines except perhaps some stratiform base metal deposits). **Long-hole open stoping** (a common method in Canadian mines for steeply dipping orebodies) generally uses backfill to stabilize adjacent stopes, but the amount of fill (and cement) can be less than in a true cut-and-fill operation. These nuances mean there's a **spectrum of energy intensity within underground mines** – with **highly selective, heavy-backfill methods on the higher end** (more energy per tonne) and **bulk, caving methods on the lower end** (less energy per tonne). All underground mines will share certain overheads like ventilation and pumping, but those overheads are amortized over many tonnes in a caving operation, whereas in a small-scale cut-and-fill they loom larger per tonne of ore.

- **Equipment Differences:** Different underground methods use different fleets of equipment, which can shift energy use from diesel to electric. For example, a **block cave** might use electric rock loaders (LHDs) and extensive conveying systems (often electric-driven) to handle ore, whereas a small cut-and-fill mine might rely on diesel trucks and loaders for haulage in confined spaces. Also, a **mine using backfill** will have pumps and motors running the backfill plant (electricity consumption), whereas a **caving mine** might invest more in underground crushers and conveyors (also electric, but contributing to a different distribution of energy use). These differences can be captured in LCI if data is available – e.g. tracking **diesel vs electricity split** in energy use. In many cases, the **electricity share is higher in backfill mines** (due to backfill plant, more rock hoisting per tonne of product, etc.), while **diesel share might be relatively higher in caving mines** (which often involve moving broken ore with diesel loaders/trucks from drawpoints) [16] [17]. The cited study indeed observed caving-based cases used *more diesel per tonne* than backfilling cases, but far *less electricity*, netting an overall lower energy use [13].

Differences Among Surface Mining Subcategories: For metals in Canada, "open-pit" is a fairly uniform category (mostly truck-and-shovel as mentioned). There might be a few distinctions: for example, a **large open-pit** with long haul distances will burn more diesel per tonne than a small quarry with short hauls. Some surface mines use **conveyor belts or rail for part of material transport** (which would shift some energy to electricity), but this is not very common in Canadian metal mines (it's seen more in certain large iron or coal mines elsewhere). **Placer mining** (like sluicing/dredging alluvial gold) if considered, has a different profile: it uses lots of water flow (pumps) and typically diesel for excavators, but usually on a much smaller scale of operation – its energy per kilogram of gold might be high, but those operations are minor compared to big open pits. **Strip mining** (continuous removal of shallow strips) is not typical for metals but is similar to open-pit in equipment and energy use. Overall, within surface mining of metals, the **variation in LCI is more due to scale and geology (e.g. the strip ratio, haul distance, and ore hardness affecting processing energy) than the named mining method**. That is, two open-pit mines might differ greatly in energy use if one has to move 3 tons of waste per ton of ore and the other moves 8 tons of waste per ton of ore, even though both are "open-pit" mines. These factors might be handled separately in your model (perhaps via deposit type or ore grade variables), but it's worth noting that **the open-pit vs underground distinction is a primary driver of energy differences**, with open pits usually at an energy disadvantage because of the large mass of material moved [5].

In summary, **yes, the mining method subcategories do have different consumption patterns**. To recap the main points with supporting data:

- **Open-Pit vs Underground:** Open-pit mining generally consumes *more energy per unit of product* and relies heavily on diesel fuel, largely because of the **greater material (rock) moved per unit of ore or metal** [5]. In a benchmark study, open-pit operations averaged ~26 GJ/ton copper vs ~16 GJ/ton for underground – illustrating the impact of method on energy intensity [6]. Open pits also produce far more waste rock, which can indirectly lead to more ancillary energy use (e.g. longer waste transport, larger tailings management needs). Underground mines, while requiring ventilation and hoisting (electricity intensive), avoid most of the mass excavation of waste, giving them a potentially smaller footprint in LCI for equivalent output.

- **Within Underground:** A bulk **caving method** can be almost as efficient as an open pit in terms of unit energy, but with a different energy profile (more electricity, less diesel) and generally **lower overall energy use than selective methods** [3] [13]. **Selective stoping with backfill** tends to be the most energy and material-intensive approach (high cement usage, more electrical energy for backfill and ground support, etc.) [10] [11]. Empirical LCA comparisons back this up: caving-based mines showed ~15–20% lower energy per tonne and much lower CO_2 emissions than backfilling mines in one study, due to **elimination of backfill operations and lower electricity needs** [13] [14]. This indicates the subcategories are indeed relevant to LCI.

- **Material Use:** Aside from energy, consider **material consumption**: Methods requiring backfill consume significant **cement and aggregate** (for paste fill), which adds to the **upstream environmental burden** (cement manufacturing is energy- and carbon-intensive). For example, cement for backfill is cited as a major contributor to the carbon footprint of underground mines using cut-and-fill [10]. Other materials like ground support (steel rock bolts, timber, shotcrete) are used in all underground mines but more so in highly fractured or unsupported methods – not a huge driver in LCI compared to fuel and electricity, but still something. Open pits use relatively less support materials (since slopes are stabilized primarily by geometric design and some rock bolting on highwalls). Instead, open pits consume other materials like large tires, explosives, etc., in greater quantities. **Explosives** usage can also differ: open pits typically use enormous amounts of explosives to blast rock (because they mine large volumes in the open), whereas an underground mine blasts smaller volumes in confined stopes. However, underground may use a higher *explosive intensity* per ton of ore in some cases (because very hard ore or precise blasting), but usually the total explosive per ton of final product is still higher in open pit due to all the waste rock blasted. These nuances can be included in an LCI if data permits (e.g. kilograms of ANFO per ton rock for each method).

Does It Make Sense to Use Subcategories in LCI Modeling?

Relevance vs. Practicality: Incorporating mining method subcategories into your LCI archetype model can **improve accuracy**, because as shown above, an underground mine with cut-and-fill will have a different environmental profile from an open-pit mine or a block-caving operation. If your goal is to model life-cycle impacts of metal mining as closely as possible for **all active Canadian mines**, capturing these distinctions is valuable. For instance, if you lumped all underground mines together, you might **underestimate** impacts for those that use a lot of cemented backfill, or **overestimate** impacts for a large block-cave mine. Differentiating subcategories allows the model to reflect that, for example, *"Underground-Caving" mines might use less energy per ton and emit less CO_2 than* "Underground-Backfill" *mines given the same ore throughput*. It also lets you account for differences in **energy types** used (diesel vs electricity) which is important if, say, you are concerned with fuel-related emissions or power-related impacts separately.

However, one must balance this with data availability and complexity. You mentioned that you have detailed labels from MiningDataOnline but are unsure how to group them. A practical approach is to **map each detailed mining method to a broader category** as discussed. For each mine, you could assign: - "Open Pit" if it's primarily surface mining (maybe even quantify if it's 100% open pit or mixed), - "Underground – Caving" if terms like *block caving* or *sublevel caving* appear, - "Underground – other" (stoping) if it's underground but without mention of caving (e.g. methods like long-hole, cut-and-fill, room-and-pillar, etc.). If you want to be more granular, you could further sub-label the underground "other" category into "with backfill" vs "without backfill" – perhaps based on whether methods like cut-and-fill (which definitely use backfill) are listed. **Cut-and-fill** or **shrinking stoping** usually imply backfill, whereas **room-and-pillar** or **open stoping with pillars** might imply minimal backfill. This might be possible if the data lists the specific methods.

From an LCI perspective, the **biggest leap in accuracy comes from separating surface vs underground** [5]. Many life-cycle studies treat those as fundamentally different scenarios, given the stark differences in waste handling and energy use. **Subdividing underground methods further** can refine the model: as evidenced, a division between high-productivity bulk mining and selective mining will correlate with energy and material intensity differences [3] [13]. If your dataset and time allow, it is sensible to incorporate that. The differences are real (as we've cited), though not as extreme as the open vs underground dichotomy. For example, an underground caving operation could have an energy intensity somewhat akin to a (efficient) open pit mine, whereas a small cut-and-fill operation could have energy intensity several times higher per tonne. Including subcategories helps capture that range.

All Active Mines in Canada – Considerations: Since you are covering all active mines, keep in mind: Canada's mines vary widely by commodity and scale, which often correlates with mining method. For instance: - Large low-grade base metal deposits (e.g. porphyry copper mines, iron ore mines, diamond mines) tend to be open-pit (with some transitioning to underground block cave when they go deep, e.g. the Argyle diamond mine example internationally, or planning for block cave at Canada's Diavik diamond mine underground phase). - Gold and high-grade base metal deposits are often underground (many gold mines in Ontario/Quebec are underground, using long-hole stoping or cut-and-fill). - Potash mines in Saskatchewan include conventional **underground room-and-pillar** mines and some **solution mining** facilities – if you include those, solution mining (pumping brine) would be another category with its own profile (high electricity for pumping and gas for evaporating water, etc., quite different from digging rock). - Uranium mines in Canada (like Cigar Lake, McArthur River) are technically underground and use non-standard methods (jet-boring with freeze walls) – those might be unique but can be lumped under underground for broad LCI, noting they have unusually high energy needs due to water inflow management and freezing (if you have such data).

The key point is that **method often aligns with deposit type and ore characteristics**, which you are already analyzing. Incorporating method subcategories will complement your deposit type and ore type data. For example, if a deposit is a vein gold deposit, it's likely an underground stoping method – high-grade, lower tonnage, higher energy per tonne. A porphyry copper is likely open-pit – low grade, massive tonnage, moderate energy per tonne but huge absolute energy. A kimberlite pipe (diamond) might be open-pit then block cave – you'd handle it as a hybrid (perhaps split the life cycle phases or choose the dominant). Having method categories helps assign the right energy and material intensity factors to each mine archetype.

Data and LCI Parameterization: If you have access to data like energy consumption (or even proxy data like mine production rate, equipment types, etc.), you can calibrate your archetypes. For instance, you could assume an archetypal open-pit mine uses X liters of diesel per tonne of ore and Y kWh of electricity per tonne, whereas an archetypal underground-caving mine uses a different ratio (more kWh, less diesel) and an underground-cut-and-fill uses yet another (plus Z kg of cement per tonne of ore for backfill, etc.). The references provided support such distinctions: e.g. an underground mine might use roughly **40% of its energy as electricity (for ventilation) and 60% diesel** [8], and a backfilling mine will also use cement (~5–15% of its carbon footprint was cement in the cited study) [10]. Open pits might use **>90% of mine-site energy as diesel** [7] and very little cement (maybe some for infrastructure but not for backfill). These differences absolutely affect LCI outputs (GHG emissions, etc., since grid electricity vs diesel combustion have different footprints, and cement has its own CO_2 cost).

In conclusion, for **point (2)** of your question: it does make sense to look at subcategories in the context of LCI **if you have or can reasonably estimate different consumption patterns for them**. The evidence shows they *do* have different patterns. The magnitude of difference is significant enough – especially between extremes like open-pit vs underground, and caving vs intensive-backfill – that your model would be more robust and representative by accounting for them. If all mines were modeled identically regardless of method, you'd lose fidelity. Given that you have data on each mine's method, you're in a good position to utilize it.

Recommendations for Grouping and Using Subcategory Data

For **point (1)**, yes, we have clarified subcategories (the detailed methods are indeed those sub-divisions of open pit or underground). For **point (3)** (covering all active Canadian mines), the approach should be to apply a consistent categorization and assign archetype parameters for each category. Here's a suggested grouping and how it ties to LCI parameters (energy, materials):

- **Open-Pit Mines (Surface)** – Characterize by high diesel use for haulage, large waste rock handling. Key LCI parameters: high fuel consumption per tonne moved, but no underground ventilation requirement; explosives usage scaled with material moved. Electricity mainly for processing plant and ancillary (minor for mine operations). No backfill; waste rock stored in dumps. **Energy intensity**: moderate-high per ore tonne (depending on grade/strip ratio) and largely fossil fuel-based.

- **Underground – Caving (Bulk Underground)** – Characterized by very high throughput underground operations (often ore body is low-grade but massive). Key parameters: significant electricity use (fans, hoists, conveyors), and some diesel (for loaders or haulage before ore reaches crushers/conveyors). **No backfill or minimal**, but will have surface subsidence. **Energy intensity**: lower per tonne than other underground methods because of economies of scale (approaching open-pit levels of efficiency) [3]. Likely still somewhat higher grid electricity fraction than open pit. Example: a block cave copper mine can produce tens of thousands of tonnes per day, using gravity flow – very efficient per unit.

- **Underground – Stoping with Backfill (Selective)** – This includes cut-and-fill and any long-hole stoping operations that use backfill extensively. Key parameters: **cement consumption** (dozens of kg of cement per tonne of ore mined, depending on backfill recipe and percentage of void filled), **higher electricity use** (running backfill plant, pumps, plus normal ventilation/hoisting), and moderate diesel (for equipment). Often these mines have lower throughput (a few hundred to couple thousand tonnes per day), so fixed energy costs (ventilation, pumping) are spread over fewer tonnes – raising per-ton energy. **Energy/impact intensity**: highest of the categories, with additional CO_2 from cement. These mines maximize metal recovery but at cost of higher LCI impacts per tonne of ore.

- **Underground – Stoping without significant backfill** – If needed, this could be a category (for mines that use pillar methods or minimal backfill). Parameters: similar to above but without cement; still require ventilation and have moderate diesel for mobile equipment. Energy intensity per tonne might be intermediate. If data doesn't allow distinguishing this from the backfill group easily, you might merge and use an average for all "non-caving underground," or use backfill as a variable in the model (e.g. add cement impacts for those mines known to use it).

- **Other categories**: If any **solution mining or dredging** operations are present in your list (not typical for most metals, except maybe *uranium solution mining or potash*), you'd handle those separately since their profiles (heavy use of electricity or natural gas for solution mining pumps and processing) differ greatly. Likewise, **placer mining** could be a small category (mostly diesel for heavy equipment, and some electricity for camp or processing, water use considerations, etc.). These might be minor overall but worth noting if completeness is needed.

Finally, for **point (4)**, you asked "*Yes if you have it*". If this was in reference to having data or references on different consumption patterns: we've included multiple sources above that **quantify the differences**. To reiterate a key reference: **Norgate & Haque (2010)** and others (as summarized by CEEC) noted the typical breakdown of energy at a mine site – e.g., in an underground copper mine with concentrator, ~55% of site energy is in mining (ventilation + diesel) and ~45% in processing, whereas in an open-pit mine ~60% is in mining (mostly diesel) [18] [7]. Another reference compared a sublevel-caving operation to a more conventional stoping operation and found the caving method to yield **lower unit energy consumption** and costs [3]. We also have the detailed LCA study of Chinese mines confirming **caving vs backfill energy and emission differences** [13] [14]. These sources support the conclusion that subcategories have different LCI profiles, and thus it's justified to use them in your archetype modeling.

In summary, leveraging subcategories will make your LCI modeling of Canadian mines more nuanced and accurate. The differences in energy (diesel vs electric), ancillary material use (cement for backfill, etc.), and overall intensity are well-documented between methods. Just ensure you have a clear scheme to group each mine into the right archetype. For all active mines in Canada, a **reasonable categorization and a set of 3–5 archetype models** (as outlined above) should capture the majority of variation in mining and processing LCI. This will allow you to assign appropriate life-cycle inventories for each mine based on its deposit type, ore type, **and mining method** – improving the fidelity of your model predictions.

Sources: The analysis above is supported by literature and industry data on mining energy use and methods (e.g. CEEC's energy benchmarking report [5] [6], the Appian advisory on sublevel caving [3], and a life-cycle assessment of underground mining methods [13] [14]), as well as Canadian mining context from

NRCan and other industry reports. The cited sources provide quantitative evidence of how mining method choice impacts energy and material consumption patterns in mining operations.

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