Green Mining for the Energy Transition

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ABSTRACT

The world's energy supply is transitioning from fossil fuels to renewable energy. The lack of certain raw materials (including lithium and others) in the volume needed for this energy transition has been identified as a potential bottleneck. Many of these raw materials are obtained through mining. Current mining processes generally use open pits to obtain these materials. The carbon footprint, water use, and land use needed to use open pits to supply the increased raw materials that will be needed for the energy transition presents a significant environmental challenge (McKinsey 2022).

The large growth in raw materials required for the energy transition will require exploring new mining processes that are greener. There is a need for mining and refining processes that eliminate greenhouse gas emissions and significant environmental damage caused by the production of these raw materials. In addition, the raw materials for the energy transition need to be chosen so that they are sufficient to supply the current needs of industrialized countries and the future needs of developing countries.

The mining, refining, and production methods currently used to produce the raw materials needed for the energy transition are based on low-cost, on demand, fossil fuel energy sources. The current methods also are based on a relatively low production growth consistent with a global demand growth of 3-4% per year. The current methods use significant amounts of low-cost freshwater. The energy transition will significantly increase the demand for the key raw materials at an increased growth rate for decades. High efficiency, high recovery, economically viable methods, using intermittent renewable energy, with low freshwater use, must be developed to support the energy transition.

EWM's Full Recovery Desalination® process technology can be applied to the mining and raw material production industries to provide a high efficiency, high recovery, economically viable solution based on intermittent renewable energy, with low or no freshwater use. The integration of state-of-the-art electrochemical technologies and green energy supply systems that EWM uses for its desalination process can be economically applied to the mining and raw materials industry.

This results in:

- Increased raw material volumes sufficient to support the energy transition
- Elimination of mining and refining wastes
- Significant reduction in water consumption
- Energy transition of the mining and raw materials industry to renewables away from fossil fuels

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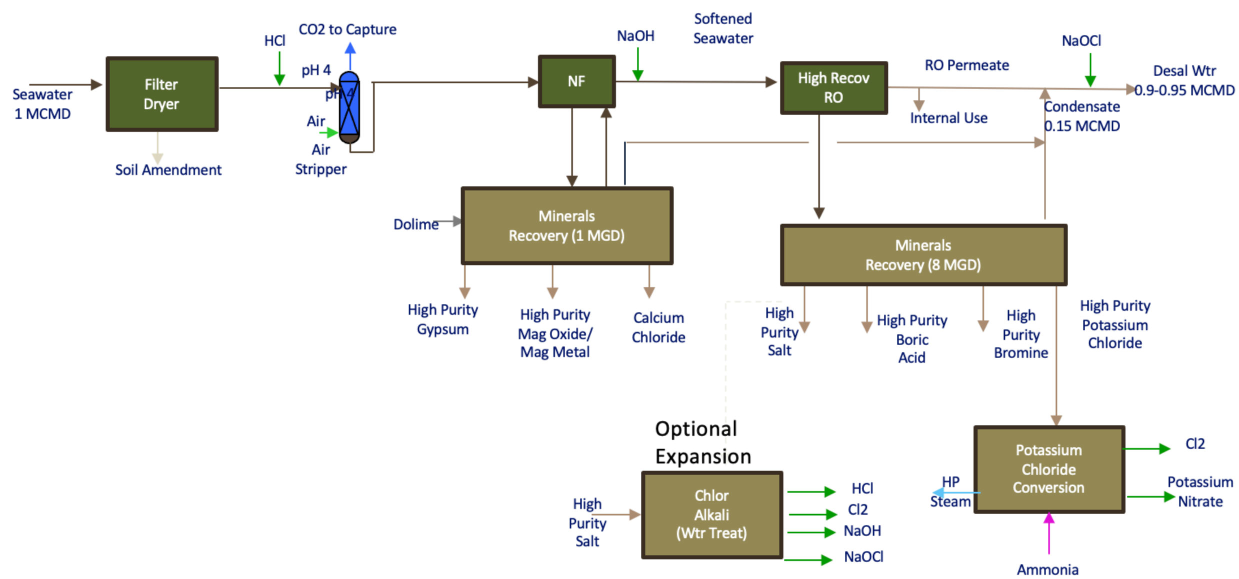
INTRODUCTION

EWM has been developing its Full Recovery Desalination® process technology for over 10 years. EWM's expertise is in integrating state-of-the-art electrochemical, membranes, ion exchange, evaporation, crystallization, and precipitation systems with renewable energy. The Full Recovery Desalination® process uses existing process equipment to separate the feed salty (high dissolved solids) water into high value commodity grade minerals. The water is essentially a byproduct of profitably recovering all the minerals.



EWM Full Recovery Desalination® for Seawater. EWM integrates commercially proven technologies from multiple industries – no "unproven technologies" and no waste streams.

Figure 1 – EWM Full Recovery Desalination® Process Block Flow Diagram

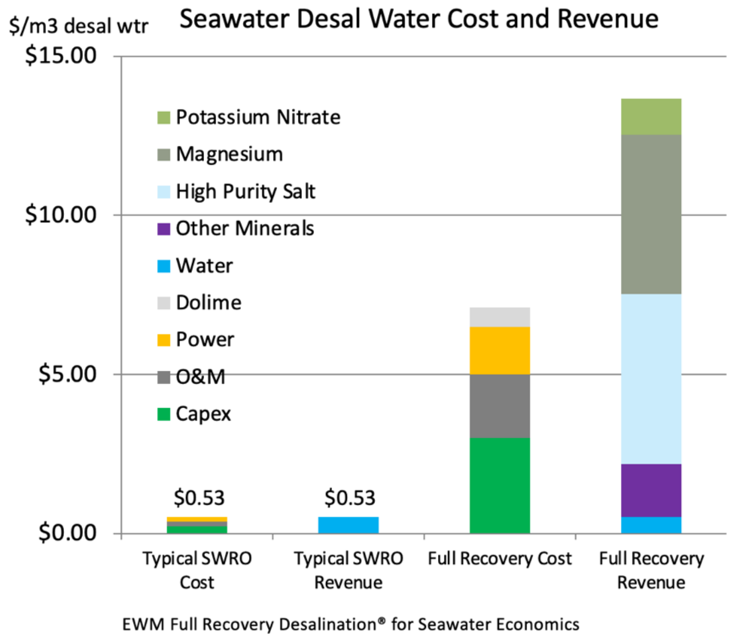
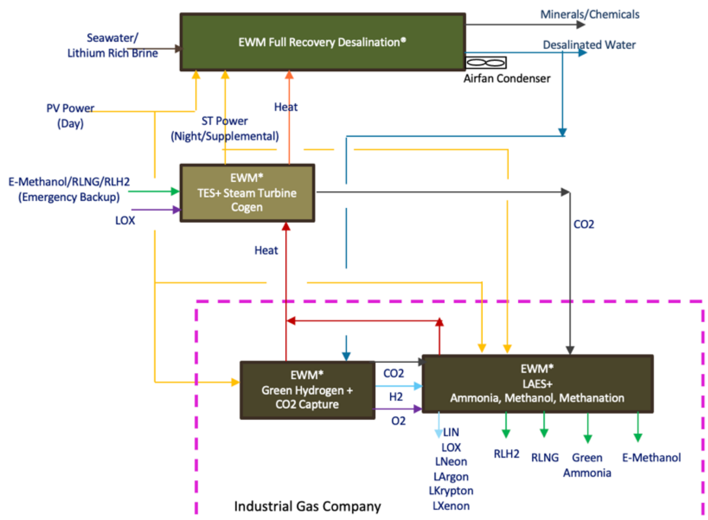


Figure 2 – EWM Full Recovery Desalination® Sample Seawater Economics

The economics shown in Figure 2 include magnesium metal production but do not include high purity chemical grade salt production. Hence, the potentially significant added value for renewable energy powered salt to chlor-alkali, green PVC, and glass production is not included. The Full Recovery Desalination® economics shown are favorable because the revenue from recovering the minerals offsets the additional capital as well as the operating and energy costs. EWM also has developed optimized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) systems to supply low-cost baseload heat and power to the Full Recovery Desalination® process from intermittent renewable energy.



* Optimized to match the desalination plant's energy requirements and low cost liquid air from LAES.

Figure 3 -- EWM's Optimized TES and LAES System for EWM Full Recovery Desalination®

A low-cost, optimized energy storage system is an important design feature of EWM's Full Recovery Desalination® process. This design feature allows for cost effective low-cost intermittent PV and wind power. Full recovery is an energy and capital intense process and, therefore, EWM has developed a customized high reliability, high efficiency system to be able to use 100% renewable energy. Using 100% renewable energy in capital intensive industrial processes such as EWM's process is challenging because the processes must operate the baseload (24/7/365) for full capital utilization.

The same brine processes and energy systems can be used in hydrometallurgical applications. EWM has recently developed process flow schemes for the mining industry to allow:

- Increased production to support the energy transition demand growth
- Higher efficiencies and yields from the same natural resources (ores and brines)
- 100% intermittent renewable energy supply system (no fossil fuels)
- Near 100% water recovery with minimal consumption and no waste brines or leachate

Nearly all the ores and brines required to produce the raw materials for the energy transition are in arid, water limited regions. Thus, components of the Full Recovery Desalination® process can be used to minimize water consumption. The arid conditions, however, allow for low-cost high availability of solar power. This can be cost effectively used for both mining and mine mouth refining using energy intensive full recovery conversion and production processes.

EWM also has developed a high efficiency, low water consumption Full Recovery Agriculture™ system (subject of a future EWM paper) to provide the required food and backup biofuels. These agricultural practices, together with the Full Recovery Desalination® process, allow sustainable communities to flourish and provide significant economic opportunities for the indigenous population at these large vertically integrated mine mouth and refining sites.

The key raw materials for the energy transition have been identified in order of percent of current global capacity as (Tesla Master Plan 2023, McKinsey 2022):

- Lithium
- Nickel
- Silver
- Zinc
- Copper
- Cobalt
- Iron/Steel
- Manganese
- Aluminum
- Graphite
- Phosphorous

One of the most critical Rare Earth Elements (REE), Neodymium also was identified as a potential raw material bottleneck for the energy transition.

In addition, the following key energy transition non-metal produced materials were identified:

- Polymers
- Glass
- Silicon
- Concrete

Each of these raw and produced material challenges for the energy transition could be met by:

- Using a renewable, energy-based full recovery process
- Substituting a less expensive greener, or higher performance, alternative material

A critical feature of optimizing material selection and product design is the ability to recycle the raw materials to minimize the raw material ore or brine that will be required to grow and maintain the global energy transition material requirements.

Lithium

Lithium Brine

More than half of the global lithium resources (estimated at 90 million tonnes) are located in: the Atacama desert region in the salt flats of Bolivia (largest global resources); Chile (largest global proven reserves); and Argentina (third largest global proven reserves) (Canadian government 2021). Sociopolitical conditions have been reported to severely limit access to Bolivia's resources, and Chile's new constitution process is ensuring that there is more government oversight and control of lithium mining. Water scarcity and resource conservation are significant issues because the lithium brine reserves are located in the Atacama desert.

The lithium recovery process currently in commercial operation is based on evaporation ponds that were initially designed to recover potassium. Pond systems are low cost, but also are low-efficiency solar powered evaporators. Essentially all the water in the brine is lost to evaporation. It is difficult to obtain high lithium recoveries from evaporation ponds due to the low lithium concentration in the feed brine and the high concentration of other "waste" salts, especially sodium chloride. Much of the lithium in the brine gets trapped in the "waste" salts.

In Chile, SQM reported only 47% of lithium was recovered in their process during 2019. Most of the lithium became part of the waste solid salt tailings. With several efficiency investments and continuous addition of purchased minerals, this company is targeting 62% lithium recovery in 2023. However, due to water table and environmental issues, SQM plans to cut feed brine extraction flows by 35% in 2028 (SQM 2022).

Bolivian brines are a much larger resource but have a much lower lithium content (less than 35% of the Atacama brine) and higher ratios of non-lithium salts to lithium (US Patent App US2022/0136081 2022). This drives low-cost evaporation pond recoveries of lithium even lower. Extraction of lithium from Bolivian brines has caused pollution issues in the past, and significant political and environmental resistance to lithium brine mining has been encountered.

Direct Lithium Extraction (DLE) technologies have been developed to selectively extract lithium from the brine. However, other valuable minerals and fresh water are not extracted, limiting the total revenue from the brine. Therefore, the total value of the brine resource is not captured and, typically, imported chemicals or fresh water must be used to perform the lithium extraction and refining. DLE technology typically has lower recoveries with lower lithium concentration brines.

EWM has developed a Full Recovery Lithium Brine Process™ for lithium brine. The process seeks recovery of multiple high purity products. In addition to battery grade lithium carbonate, the process aims to recover magnesium metal and the high value fertilizer potassium nitrate. High freshwater recovery (96%) enables co-production of green hydrogen and ammonia, which is to be oxidized to produce high pressure steam for power and heat as well as the valuable nitrate for the potassium nitrate. Alternatively, fresh water could be reinjected to maintain water table levels, and fresh water from desalinated seawater could be used for green hydrogen and ammonia.

The magnesium metal and potassium nitrate co-product revenue from this process would be significant, even with the high Chilean lithium content brines, which would represent more net revenue than the lithium after brine royalty payments. For lower lithium content brines like the Bolivian brine, the co-product revenue expected is even higher because the high value of "'interfering" components (magnesium, sodium, and potassium) are present in a much higher ratio to the lithium ions.

All of the chemicals and minerals required in EWM's Full Recovery Lithium Brine Process™ are self-supplied in a fully circular design. Low-cost Direct Air Capture (DAC) of CO2 is used to supplement the carbonate in the brine to produce the lithium carbonate product.

The critical lithium recovery factor is much higher (>98%) in the full recovery process because the purification of the coproducts recovers essentially all the lithium impurities. The diversified product slate reduces the risk of uneconomical mining. The large swings in lithium price are dampened by the more stable prices for the other high purity minerals.

The full recovery process produces a lithium rich (approximately 0.1 wt% Li) high purity chemical grade sodium chloride salt, which could be exported to a remote chlor alkali plant. EWM has developed a lithium hydroxide recovery process that integrates with existing chlor alkali plants to produce chlor alkali products (e.g., chlorine, caustic, bleach, HCl) and extract the lithium from the highly refined chemical grade salt as battery grade lithium hydroxide.

EWM also has developed a low-cost, high lithium recovery, circular conversion process that converts battery grade lithium carbonate product into battery grade lithium hydroxide and high purity CO2 stream suitable for sequestration or use in E-Fuels (e.g., Sustainable Aviation Fuel - SAF). Therefore, the lithium carbonate product can be used as a CO2 carrier to transport the CO2 to a geologically suitable location for sequestration or to SAF production facilities. No tailings, or waste brine effluents will be produced from the process, and no chemical addition is required.

The Full Recovery Lithium Brine Process™

The process EWM has developed consists of the following treatment steps:

- Pretreatment and minerals precipitation

- Magnesium metal production
- NaCl and KCl salt recovery
- DAC and lithium carbonate recovery
- Onsite and remote chlor alkali
- Remote lithium hydroxide production
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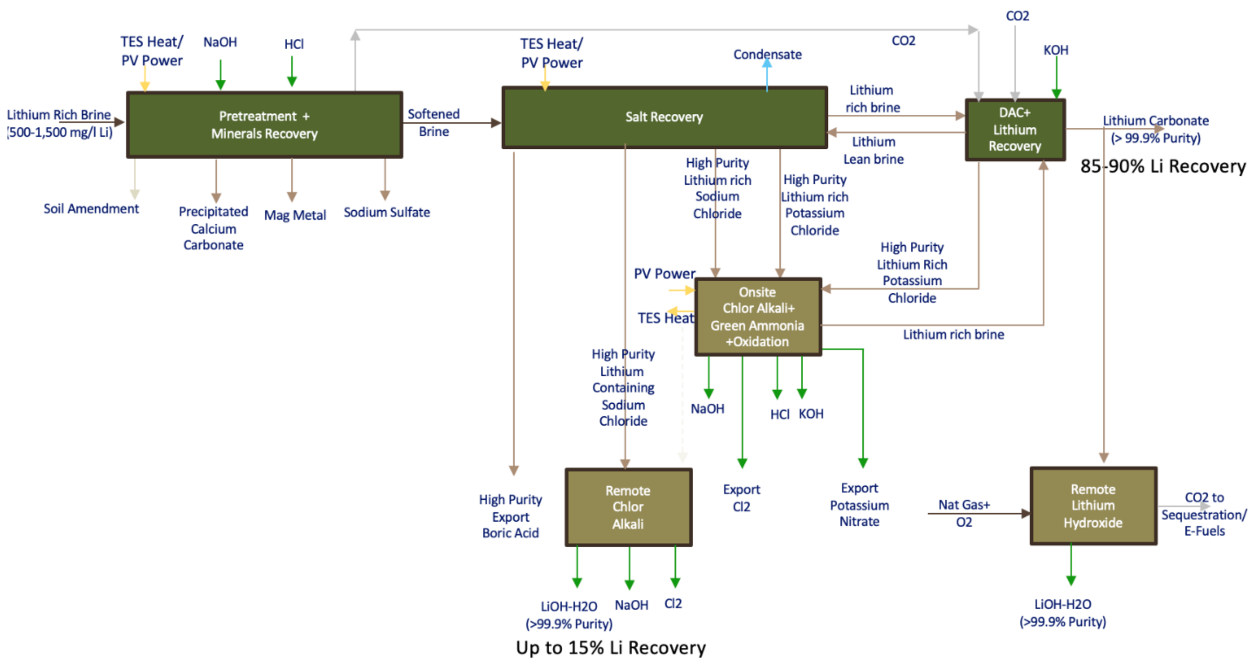
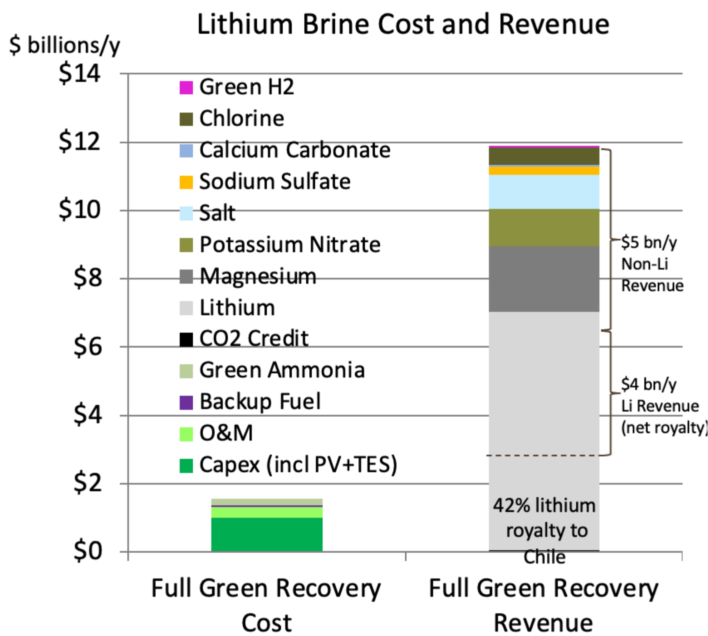


EWM Full Recovery Lithium Brine™ – 99% Lithium recovery with no "imported chemicals", no "waste tailings", and carbon capture from the atmosphere

Figure 4 -- EWM Full Recovery Lithium Brine Process™ Flow Diagram

The Full Recovery Lithium Brine Process™ uses more energy and will require more capital than evaporation ponds or DLE; but the incremental revenue expected from the diversified product slate should more than compensate for the additional costs. No chemicals or minerals will be needed to be imported for the process, and DAC is used to produce the carbonate used to produce the battery grade lithium carbonate. This allows the entire process to be carbon negative because it uses low-cost self-supplied solar power and DAC CO_2 to produce lithium carbonate (avoiding release of CO_2 from the mining, refining, and transportation of mined carbonates – trona or limestone).



*Based on 100,000 m3/d 0.15 wt% Li brine extraction (400,000 tonnes/y Li2CO3 equivalent) priced at $18,000/tonne (40% estimated 2027 global demand, 25% 2022 market price). Excludes industrial gases and green H2 conversion to ammonia.

Figure 5 -- EWM Full Recovery Lithium Brine Process™ Sample Economics

The economics include the small onsite chlor-alkali for self-production of required chemicals but exclude the large remote chlor-alkali economics and the remote lithium carbonate conversion to lithium hydroxide with CO2 sequestration or sale to SAF.

The lithium brine resource located in the Atacama desert has the best solar resource in the world. This allows the low-cost power to produce the high value energy intensive product slate. The Full Recovery Lithium Brine Process™ makes full use of the valuable brine resource, including the water that is recovered as fresh water (96% recovery). The water can be recovered as high purity water, which allows the production of green hydrogen and green ammonia, further monetizing the solar resource. Alternatively, the water can be reinjected to maintain water tables. EWM's high water efficiency Full Recovery Agriculture™ system also may be possible, but the water flow would need to be supplemented by desalinated brackish groundwater or seawater using EWM's Full Recovery Desalination® process technology.

The significant additional investment and revenue provides more jobs and follow-on production opportunities. These could include domestic fabrication of photovoltaic modules to provide power for lithium brine mining and other co-located power intensive products (e.g., solar glass, silicon, PVC-glass composites, PV modules, etc. – See Copper below). Thus, the full recovery lithium production would bring significant follow-on investments to capture the full value chain for all the minerals in the brine, fully monetizing the world class lithium brine and solar resource.

EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources for the processing of the lithium brine. This allows all the products to be green (CO_2 emissions free, and fossil fuel free). Liquid hydrogen can be generated as part of the LAES system, which provides cost competitive fuel for fuel cell/battery hybrid mining trucks and locomotives.

Lithium in Spodumene

Spodumene is the primary lithium resource in Australia (largest global lithium producer, second largest global lithium proven reserves) (Canadian government 2021). EWM's Full Recovery Desalination® process can be modified to integrate with the sulfate free spodumene refining process to monetize the tailings and provide green feedstock chemicals (lime and soda ash).

This allows the spodumene process to be waste free and have no CO_2 emissions associated with the feedstock chemicals.

The economic benefits of the integration of the spodumene refinery with the full recovery add-on plant are as follows:

- Avoided spodumene concentrate tailings disposal
- Sale of tailings more than offsets the cost of the spodumene refinery's lime and soda ash

The Spodumene concentrate tailings are used as one of the feedstocks to produce byproduct solar glass. High purity CO_2 is produced from a hybrid renewable power/natural gas oxyfuel glass kiln, which can be used for SAF or sequestered. Green solar glass is one of the key products identified as a potential bottleneck for the energy transition (PV modules).

Renewable energy can be used in the processing of the spodumene tailings, which can be supplemented with self-produced Electro-methanol or green H2 (E-methanol/green H2 - optional backup). EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources. This allows all the products to be green (CO_2 emissions free and fossil fuel free). Liquid hydrogen can be generated as part of the LAES system, which provides cost competitive fuel for fuel cell/battery hybrid mining trucks and locomotives.

Nickel

Australia and Indonesia are the global leaders in nickel reserves. Brazil, New Caledonia (Pacific islands near eastern Australia), and the Philippines also have significant nickel reserves. Cobalt reserves also are associated with nickel production, especially for Australia, Indonesia, and the Philippines. These countries also have good (Brazil, Indonesia, Philippines) to excellent (Australia) solar power resources. The equatorial location of Indonesia, Brazil, New Caledonia, and the Philippines compensates for their non-arid climates. In addition, Indonesia has some of the world's best geothermal sites because of its volcanic geology. Energy intense nickel mining and refining should take advantage of these low-cost renewable resources to produce the significant amount of nickel and cobalt required for the energy transition.

Nickel containing ore occurs in two types of deposits: nickel sulfide from magmatic sulfide deposits and weathered nickel laterites (nickel oxide). Approximately 70 per cent of the world's nickel reserves are found in the form of laterites, which typically contain an upper limonitic (iron oxide matrix) section and a lower saprolitic (iron, magnesium silicate matrix) section. Many of the laterite reserves remain untapped due to the poor economics of extraction and the generation of large amounts of wastes.

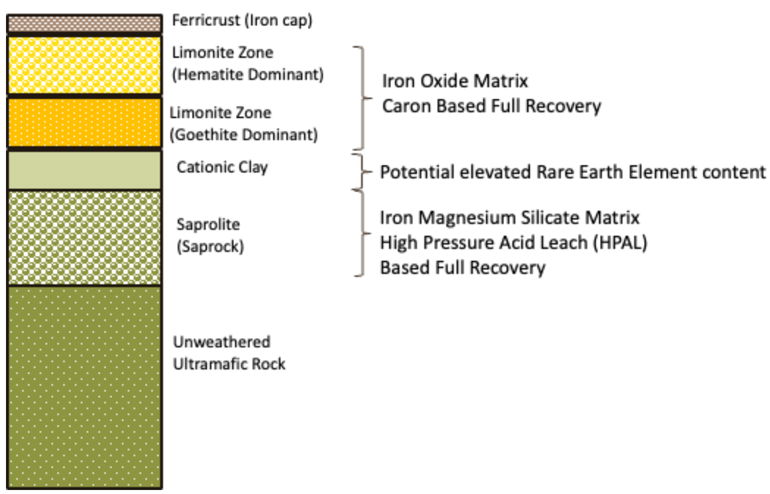


Figure 6 -- Typical Nickel Laterite Deposit Layers

Traditional nickel laterite processing techniques use large quantities of sulfuric acid at high temperatures and pressures, resulting in expensive treatment of the waste tailings and spent leachate used in the extraction process. Nickel laterites are becoming a priority for mining companies as traditional nickel sulfide reserves are depleted. In 2010, global nickel production from laterites exceeded nickel sulfide-based production for the first time (CSIRO 2023, Geology for

Investors 2014). Nickel sulfide reserves are primarily in Australia and nickel laterites are primarily in tropical regions (Indonesia, Brazil, New Caledonia).

Nickel Refining

EWM has three versions of its Full Recovery Nickel Process.™ The first process integrates with the Sherritt Gordon process for nickel sulfide ore concentrates; the second process integrates with the Caron process for the limonitic section (typically upper section) of the nickel laterite ores; and the third process integrates with the High-Pressure Acid Leach (HPAL) for the saprolitic section (typically lower section) of the nickel laterite ores.

In addition to recovering the major minerals (nickel, cobalt, iron, silica, magnesium), the Full Recovery Nickel Process™ also can recover Rare Earth Elements (REEs) that may be concentrated in the saprolitic section of the laterite ore. The REE concentrations in the saprolitic section of the laterite ores are typically not high enough for economically viable recovery with conventional nickel processing (Ore Geology Reviews 2016). Full recovery, however, may allow economic REE co-production.

Nickel Sulfide Ore Concentrates

The Sherritt Gordon process is typically used to refine nickel sulfide ore concentrates and extract nickel as a high purity metal powder. This extracts nickel and cobalt from the ore concentrate as an ammonia sulfate complex. The nickel is reduced to nickel metal powder using green hydrogen and separated from the leachate. The nickel metal powder is oxidized, reacted with sulfuric acid, and crystallized to form high purity battery grade nickel sulfate. The cobalt and residual nickel are recovered from the leachate, separated, and crystallized as a battery grade nickel sulfate and cobalt sulfate. The ammonia is recovered from the lean leachate and recycled back to the Sherritt Gordon process. The sulfate is recovered from the lean leachate as sulfuric acid and used to produce the nickel sulfate and cobalt sulfate products. Wet tailings also are produced as a byproduct of the primary nickel refining process.

The EWM Full Recovery Nickel Tailings Process™ (common to both nickel ore types) recovers essentially all the minerals and water in the nickel tailings slurry from either refining process. The minerals are recovered as high volume, high value minerals, chemicals, and green raw materials, which provides the bulk of the revenue required to make the overall tailings recovery process economically profitable.

EWM Full Recovery Nickel Process™ – Nickel Sulfide Ore Concentrates

The EWM process consists of the following treatment steps:

- Sherritt Gordon Nickel Refining to produce high purity nickel powder
- Oxidative acidic leaching and crystallization to produce battery grade nickel sulfate
- Recovery of residual nickel and cobalt from Sherritt Gordon Nickel refining leachate
- Recovery of ammonia and sulfuric acid from leachate
- Digestion, separation, and crystallization of recovered nickel, cobalt, and manganese into battery grade sulfate salts

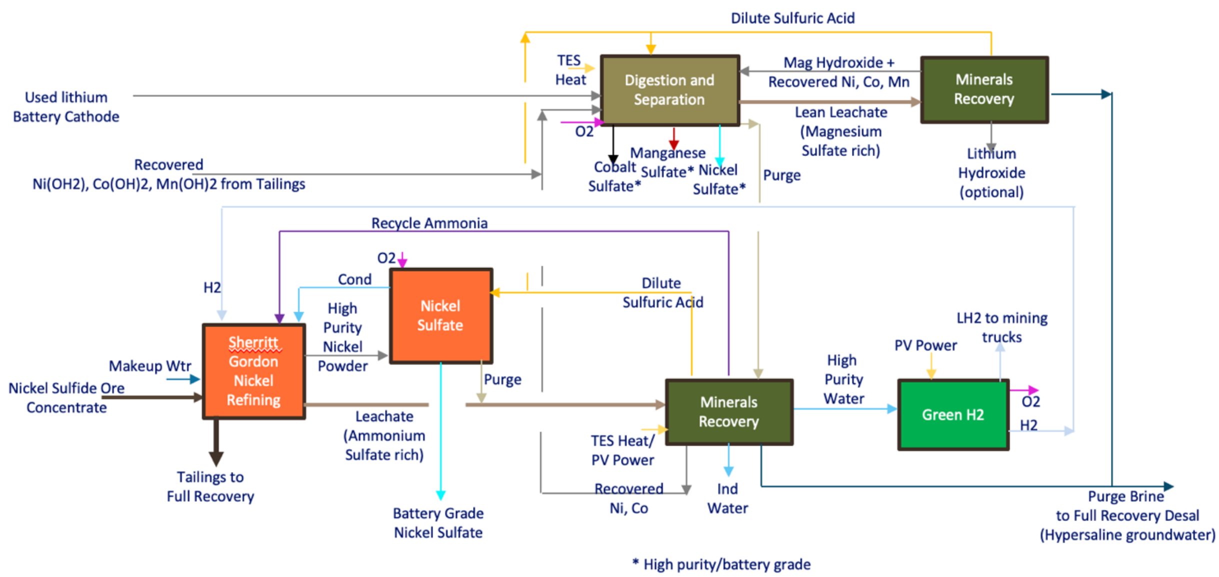


Figure 7 -- EWM Full Recovery Nickel Process™ Block Flow Diagram for Primary Minerals Recovery – Nickel Sulfide Ore Concentrate

Tailings Process (common to both Nickel Sulfide and Nickel Laterite):

- Separation of Tailings from Sherritt Gordon and Caron Nickel refining
- Minerals recovery from tailings leachate
- Green steel production
- Green glass production
- Green silicon production
- Green hydrogen production
- E-methanol production

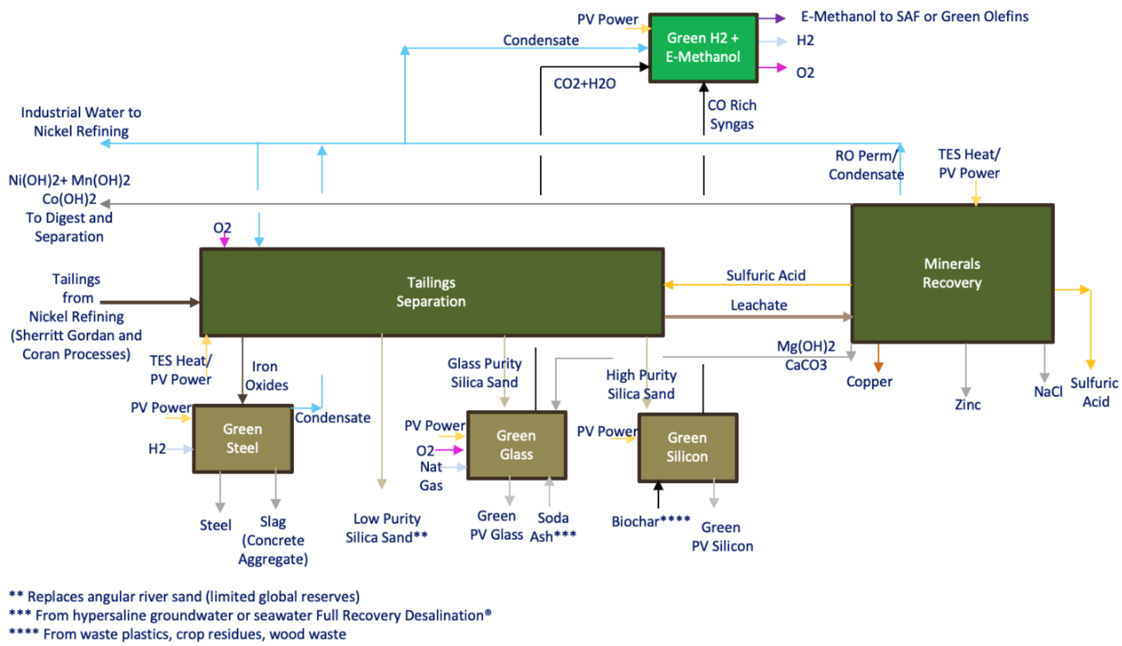


Figure 8 -- EWM Full Recovery Nickel Process™ Block Flow Diagram for Tailings Minerals Recovery

Limonitic Nickel Laterite Ore

The Caron process is used to reduce the nickel laterite (Nickel oxide) ore with heated (TES and PV power) green hydrogen to extract nickel and cobalt as soluble ammonia carbonate complexes to produce a separate iron oxide precipitate, similar to the Sherritt Gordon process (ammonia carbonate complexes instead of ammonia sulfate complexes). The extracted nickel and cobalt are separated and crystallized as high purity battery grade nickel sulfate and cobalt sulfate salts. The ammonia carbonate solution is recovered from the lean leachate and recycled to the leaching step. Wet tailings also are produced as byproducts of the nickel refining process.

The EWM Full Recovery Nickel Tailings Process™ (common to both nickel ore types) recovers essentially all the minerals and water in the nickel tailings slurry from either refining process. The minerals are recovered as high volume, high value minerals, chemicals and green raw materials, which provides the bulk of the revenue required to make the overall recovery process economically profitable.

EWM Full Recovery Nickel Process™ – Limonitic Nickel Laterite Ore

The EWM Process consists of the following treatment steps:

- Caron Nickel Refining to produce nickel and cobalt ammonia carbonate complexes

- Solvent extraction, and crystallization to produce battery grade cobalt sulfate
- Stripping to produce a basic nickel carbonate (mixed nickel carbonate/hydroxide) and to recover the ammonia
- Sulfuric acid digestion and crystallization to produce battery grade nickel sulfate and CO2, which is recycled to the Caron Nickel Refining process
- Green hydrogen production for the Caron Nickel Refining reducing multi-hearth furnace

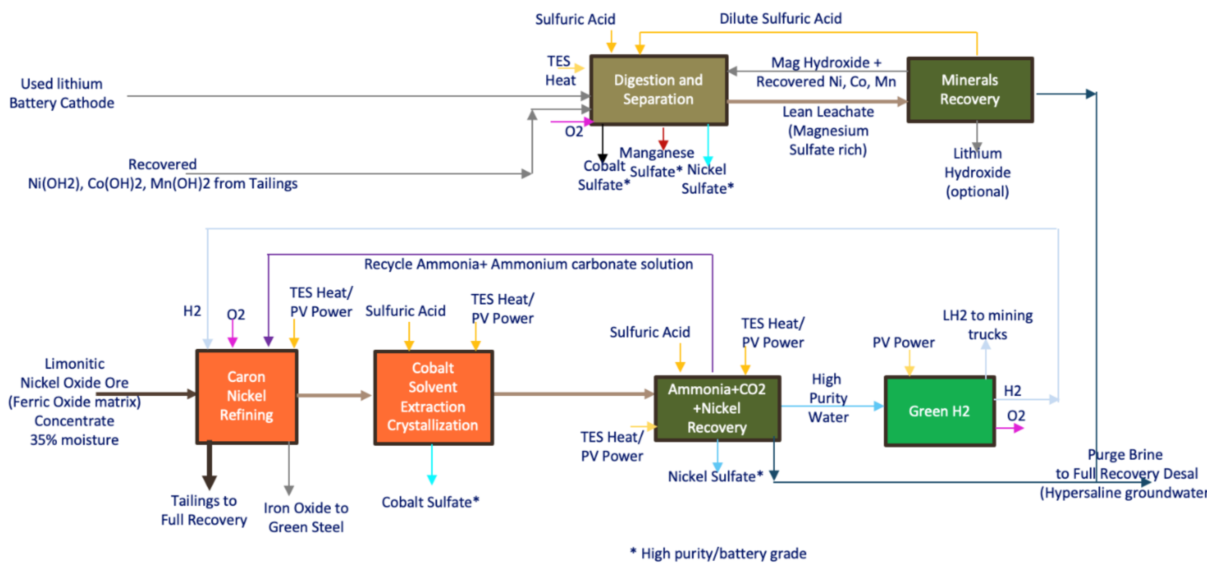


Figure 9 -- EWM Full Recovery Nickel Process™ Block Flow Diagram for Primary Minerals Recovery – Limonitic Nickel Laterite Ore

Tailings Process (common to both Nickel Sulfide and Nickel Laterite):

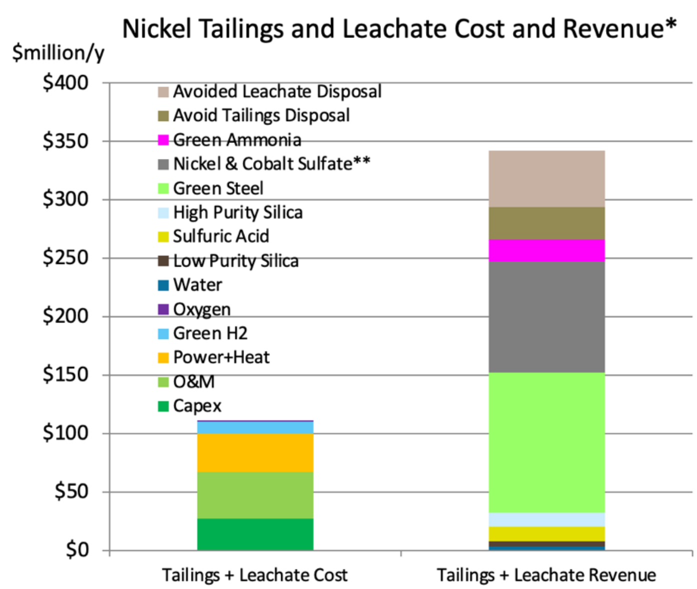
- Separation of Tailings from Sherritt Gordon and Caron Nickel refining
- Minerals recovery from tailings leachate
- Green steel production
- Green glass production
- Green silicon production
- Green hydrogen production
- E-methanol production

All the equipment that EWM uses in its unique process is commercially proven with performance guarantees from the various equipment suppliers.

The only input mineral required for either version of the Full Recovery Nickel Process™ is biochar, which is produced from waste plastics, crop residues, and wood waste. Biochar can be cost effectively transported by rail, similar to coal (the fossil fuel that it replaces). All the carbon in the biochar, the feed tailings, and leachate (carbonates) are captured and exported as E-Methanol, which can be used to generate high growth Sustainable Aviation Fuel or green olefins.

All of the nickel, cobalt, and manganese in the feed is ultimately converted to battery grade nickel sulfate, cobalt sulfate, and manganese sulfate. All the iron in the tailings is ultimately converted to green steel using onsite generated green hydrogen. All the silica, magnesium oxide, calcium oxide, and alumina in the tailings is converted to concrete aggregate (slag), sand for concrete, green PV glass, or green solar grade silicon. The copper is captured as a high value metal. Any excess sulfur is ultimately converted to sulfuric acid.

The full recovery of the byproduct cobalt is an important benefit of the Full Recovery Nickel Process™ due to potential problems in cobalt supply from the Democratic Republic of Congo (DRC) (majority of cobalt reserves and production) because of sociopolitical issues (see Cobalt below). Eliminating the loss of byproduct cobalt to the waste tailings may be as important as nickel recovery from the tailings due to the importance of a reliable cobalt supply for Lithium Ion Battery (LIB) production (see Battery Cathode Recycle below).



*Based on 100,000 tonnes/y nickel sulfate production (BHP Nickel West) excludes green H2 and O2 production (third party purchase)
** Battery grade
*** Onsite generation from high purity water

Figure 10 -- EWM Full Recovery Nickel Process™ Sample Economics (the economics includes the waste leachate and tailings but excludes: primary nickel production and conversion to nickel sulfate (typically existing facilities at nickel refineries), green glass, green silicon, green hydrogen, methanol, and PVC)

No waste brine or solids are produced – everything in the feed tailings and leachate is monetized as a high value commodity chemical or mineral. Essentially all chemicals are self-produced from effluent streams. Sulfuric acid may be imported or exported to meet the overall sulfur balance needs of the high value sulfate products.

Saprolitic Nickel Laterite Ore

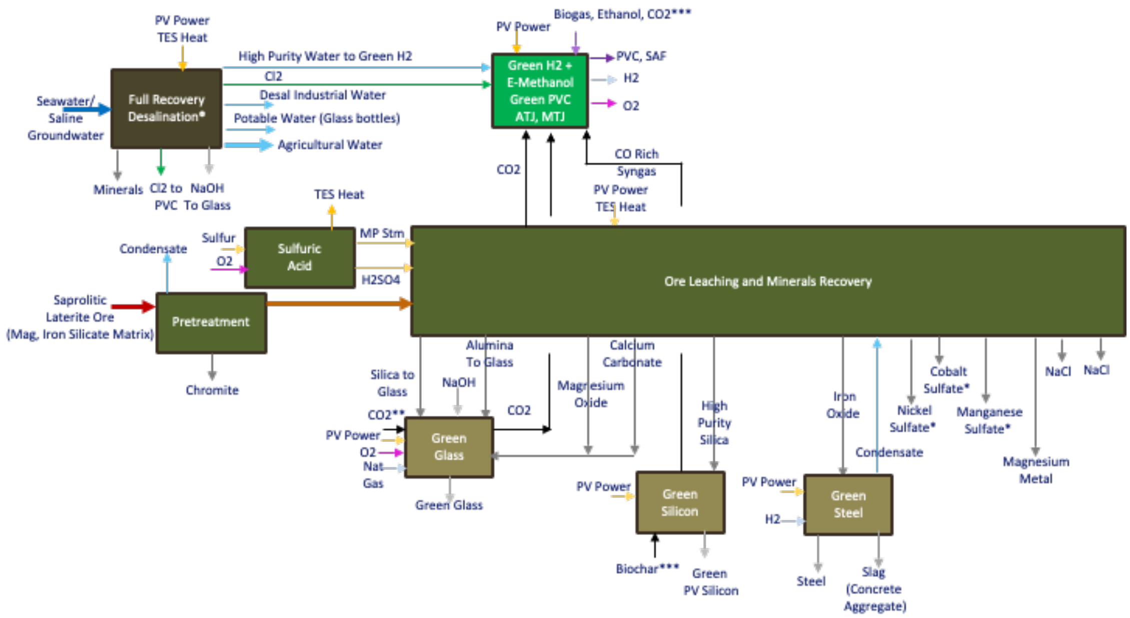
The EWM Full Recovery Nickel™ process for saprolitic nickel laterite ore digests the pretreated (ground, beneficiated, dried) ore in sulfuric acid at elevated temperature and pressure (250 C, 50 Bar). This dissolves the iron, nickel, cobalt, and magnesium as a sulfate brine which is routed to a minerals recovery section. In the minerals recovery section, the metals are separated by sequential precipitation. Sulfate is recovered from the lean leachate as sulfuric acid and recycled. It is also used to produce high purity, battery grade nickel sulfate and cobalt sulfate. Silica, iron oxide, magnesium oxide and calcium carbonate products are also recovered. A portion of the silica and magnesium oxide together with the calcium carbonate and sodium hydroxide (from seawater or saline groundwater desalination – see below) are converted to green glass. The iron oxide is converted to green steel. The higher purity magnesium oxide is converted to magnesium metal, and the higher purity silica converted to silicon. A REE concentrate may also be produced depending on REE content in the saprolitic ore body or adjacent cationic adsorption clay.

The EWM Full Recovery Nickel Process™ recovers all the minerals and water in the saprolitic nickel laterite ore. The minerals are recovered as high volume, high value minerals, chemicals and green raw materials which provides the bulk of the revenue required to make the overall recovery process economically profitable.

EWM Full Recovery Nickel Process™ – Saprolitic Nickel Laterite Ore

The EWM Process consists of the following treatment steps:

- Sulfur conversion to make up sulfuric acid and medium pressure steam
- Digestion of saprolitic nickel laterite ore
- Hydroxide sequential precipitation of metals
- Separation of mixed hydroxide precipitate and crystallization of battery grade nickel sulfate and cobalt sulfate
- Recovery of sulfate as sulfuric acid
- Green glass production
- Green steel production
- Green hydrogen, E-Methanol, and green PVC

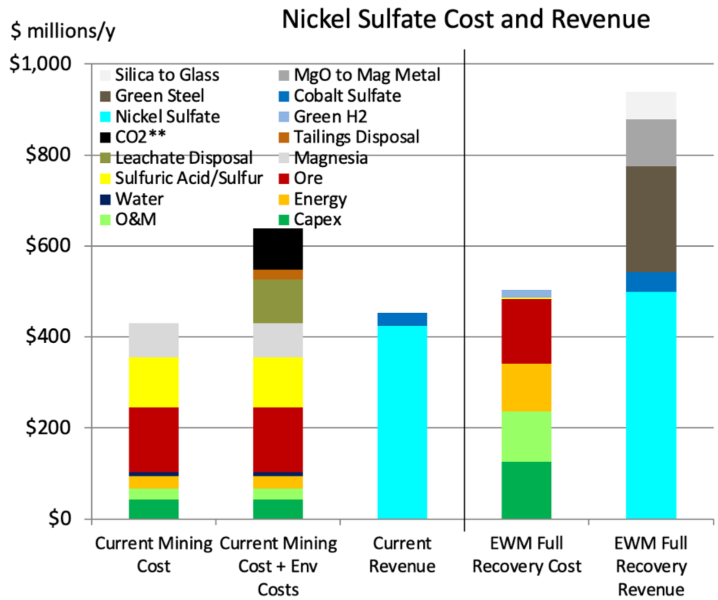


* Battery Grade
** From industrial source (e.g., cement plant) or direct air capture
***From Full Recovery Agriculture™

Figure 11 -- EWM Full Recovery Nickel Process™ block flow diagram - Saprolitic Nickel Laterite Ore

An EWM Full Recovery Desalination® unit is used to desalinate seawater or saline groundwater to provide industrial water for the nickel processing plant, high purity water for green hydrogen, and agricultural water for EWM Full Recovery Agriculture™. In addition, it provides sodium hydroxide to green glass, chlorine to green PVC and other minerals/fertilizers. The green glass, silicon, and PVC are used to produce PV modules and wind turbines domestically to provide the power required for the refining process. The EWM Full Recovery Agriculture™ system provides biochar, CO_2, biogas, and ethanol for silicon and PVC.

No waste brine or solids are produced – everything in the feed tailings and leachate is monetized as a high value commodity chemical or mineral. Essentially all chemicals are self-produced from effluent streams. Only sulfur is imported to meet the overall sulfur balance needs of the high value nickel and cobalt sulfates.



*Based on 100,000 tonne/y nickel sulfate production from Saprolitic Nickel Laterite ore
** From magnesia production and boiler

Figure 12 -- EWM Full Recovery Nickel™ Sample Economics (Saprolitic Nickel Laterite Ore)

The economics include sulfuric acid production, ore HPAL, minerals recovery, and green steel. The Full Recovery Desalination® (seawater) is excluded, which should have similar or better economics to the EWM Full Recovery Desalination® Seawater economics in Figure 2. The green glass, green silicon, green hydrogen, methanol, and PVC economics also are excluded.

The economics for the current nickel and cobalt sulfate recovery are shown as a comparison to the full recovery economics. These economics show that the current once-through sulfuric acid and magnesia based leaching and sequential precipitation system is not profitable if the full environmental costs are included. This leads to disposal or release of the spent leachate and tailings into potentially damaging biospheres, including the ocean (which creates fishery and coral reef damage (Reuters 2023, BBC 2023)).

There is a high investment cost for the nickel refining, self-production of renewable power (including PV module and wind turbine raw materials and assembly), and desalinated water and Full Recovery Agriculture.™ This, however, is a durable investment because these infrastructure investments can continue operation after the regional mines are depleted using imported nickel ore. Therefore, the high capital cost of the infrastructure investment (paid for by the full domestic monetization of the regional mineral resources) will be a useful, long lived regional asset.

Significant renewable energy is to be used in the processing of the nickel, which can be supplemented with self-produced Electro-methanol or green H2 (E-methanol/green H2 - optional backup). EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources. This allows all the products to be green (CO2 emissions free and fossil fuel free). Liquid hydrogen can be generated from green hydrogen as part of the LAES system, which provides cost competitive fuel for fuel cell, battery hybrid mining trucks, and locomotives.

Battery Cathode Recycle

The predominant LIB cathode is Nickel Manganese Cobalt (NMC) with high nickel content (maximizes energy storage capacity) and a low content of lithium. NMC LIBs currently have a 65% market share and are projected to have a 90% market share by 2030 (Electronics 2023). Currently, these LIBs have 39 kg Ni, 5 kg Co, 5 kg Mn, 6 kg Li – 70% Ni (BHP 2022). Tesla is developing its new state-of-the-art high capacity 4680 battery with a nickel content target of 90% to provide maximum energy storage (Reuters 2023).

Due to the high nickel content of the new LIBs, it is critically important to recycle all of the nickel in the used cathodes. This maximizes nickel ore resources and prevents toxic nickel ions from entering the groundwater. Nickel has a very low toxicity threshold, with a recommended drinking water limit of 70 ppb (World Health Organization 2021).

There are several methods of recycling high nickel cathodes (Electronics 2023):

- Pyrometallurgy (regenerates metal alloys with high temperature processes)
- Direct regeneration (recovers cathode materials with limited reprocessing)
- Hydrometallurgy (regenerates high purity metal salts with water-based processing)

EWM Full Recovery Nickel Process™ can be enhanced with an add-on processing block that recovers the lithium as battery grade lithium hydroxide, in addition to the recovery of battery grade nickel sulfate, cobalt sulfate, and manganese sulfate. It is economically advantageous to include cathode recycling as part of the new battery metal sulfate (nickel sulfate, cobalt sulfate, and manganese sulfate) production process. This takes advantage of economies of scale and the location of the nickel refineries near low-cost renewable power.

Recycling the cathodes using EWM's hydrometallurgical based full recovery process has the following advantages:

- 100% intermittent renewable power energy source with baseload refining and recycling operation

- EWM's TES and LAES systems in nickel refining can be used as a common site utility to meet the electrical and low temperature evaporation heat requirements (no high temperature combustion heat required)
- Producing new, fully separated, battery grade feedstock salts allows battery producers to continue to optimize their cathode formulations and manufacturing processes without being constrained to recycled cathode alloys that may not meet the requirements of the newer, better performing, lower cost cathodes

Co-location of the cathode recycling facility at the nickel, cobalt, manganese refinery maximizes the value of the capital-intensive refinery. Initially, most of the feedstock will be freshly mined nickel concentrate. As LIBs become prevalent, the refinery output remains the same, but the feedstock changes to an even greater percentage of recycled feedstock instead of freshly mined nickel concentrate. The downstream battery plants have the freedom to optimize cathode formulation and feed material purity requirements. The battery plants' feedstock logistics, permitting, and discharge byproducts (potentially gypsum wallboard and CO2 for sequestration or SAF) remain the same, independent of fresh ore concentrate feed or recycled cathode feed.

Mining, refining, and recycling of the nickel can be done with renewable energy, which can be supplemented with self-produced Electro-methanol or green H2 (E-methanol/green H2 - optional backup). EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources. This allows all the products to be green (CO2 emissions free, and fossil fuel free). Liquid hydrogen can be generated as part of the LAES system, which provides cost competitive fuel for fuel cell, battery hybrid mining trucks and locomotives.

Silver

Silver is a semi-precious metal with limited ore deposits. A small amount is typically used on solar panels to collect the electrical current on the silicon panel. The best option for the green energy transition is to substitute the use of copper for silver on the panels. Two companies are currently developing copper-based solutions that have been successfully tested.

Sundrive Solar has successfully tested a copper plating technology instead of current silver screen printing technology and achieved higher efficiency. They have received initial investor funding and are scheduled to start a pilot production line this year using the copper instead of silver (PV Magazine 2022).

Fraunhofer (German research company) has developed a copper substitute for silver using a special electroplating process and a recyclable aluminum masking system. The copper substitution for silver eliminates the potential silver raw material bottleneck and also improves performance due to copper's higher electrical conductivity (Fraunhofer 2023).

Zinc

Approximately 60% of the world's zinc production is used to galvanize steel to provide corrosion protection. Steel supports for PV solar farms, wind farms, and power transmission lines use significant amounts of zinc to provide corrosion protection (Mining.com 2021).

Untreated (non-galvanized) steel can be encapsulated by corrosion proof PVC and PVC glass composites. This materials technology is used to increase frame strength for very large multi-pane windows (Rehau 2022). PVC glass composites can be extruded into large diameter hollow truss cross section pilings and towers (Shoreline Plastics 2023).

Zinc galvanizing provides corrosion resistance, but PVC-glass fiber encapsulation of steel provides strength and corrosion protection. PVC-glass fiber has a strength to weight ratio similar to aluminum and twice that of steel. Therefore, a PVC-glass fiber encapsulated steel construction (currently used for large window frames) should be a cheaper, more sustainable materials solution compared with zinc galvanized steel for the energy transition.

Glass fiber reinforced PVC is a major product from EWM's Full Recovery Desalination® process and can be produced from seawater and captured CO2. A tonne of CO2 is sequestered in the PVC per tonne of PVC. The PVC-glass fiber thermoplastic composite materials used for window frames are design to be disassembled and remelted to achieve 100% recyclability (Rehau 2022). Zinc galvanizing is slowly lost to the environment through corrosion over the life of the galvanized steel support and, therefore, cannot be recycled at the end of the galvanized steel support's life. New zinc must be added to the recycled steel to re-galvanize it.

Copper

Most of the global copper reserves and production are in arid regions (Chile, Peru, Mexico, and Australia) and are based on copper sulfide deposits (Investing Network News 2023, Visual Capitalist 2021). Copper mining uses water intensive ore separation processes and produces a significant volume of high-water content (sludge) tailings. This creates both water sourcing and tailings disposal issues. Copper tailings can produce a residual, acidic leachate containing heavy metals due to slow oxidation of the residual sulfide in the tailings (acid mine drainage).

EWM's Full Recovery Copper Tailings Process™ addresses both water sourcing and tailings disposal. Tailings from copper flotation are separated into iron oxides, silica, and leachate. The iron oxides are to be converted to green steel. The high purity silica is converted to green glass and green silicon. The lower purity silica is used for concrete replacing angular river sand, which has limited global reserves. In the mineral recovery section, the metals in the leachate are separated by sequential precipitation. The sulfate from the leach solution is recovered from the lean leachate as sulfuric acid. Copper, zinc, battery grade manganese sulfate, salt, magnesium oxide, and calcium carbonate products also are recovered. The magnesium oxide, calcium carbonate, and soda ash (from seawater desalination – see below) are converted to green glass. The iron oxide is to be converted to green steel.

The EWM Full Recovery Copper Tailings Process™ recovers all the minerals and water in the copper tailings. The minerals are to be recovered as high volume, high value minerals, chemicals and green raw materials, which provides the bulk of the revenue required to make the overall recovery process economically profitable.

EWM Full Recovery Copper Tailings Process™

The EWM process consists of the following treatment steps:

- Separation of tailings from leachate
- Oxidative acidic leaching of tailings
- Minerals recovery from tailings leachate
- Green steel production
- Green glass production
- Green silicon production
- Green hydrogen production
- E-Methanol and green PVC production
- Methanol to jet and ethanol to jet production

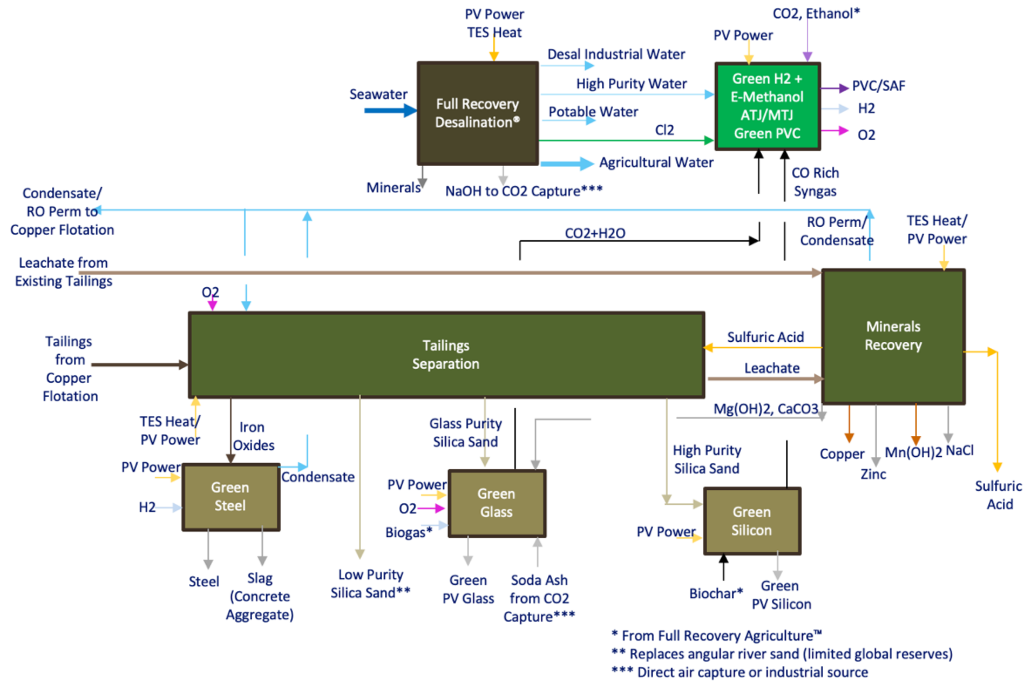
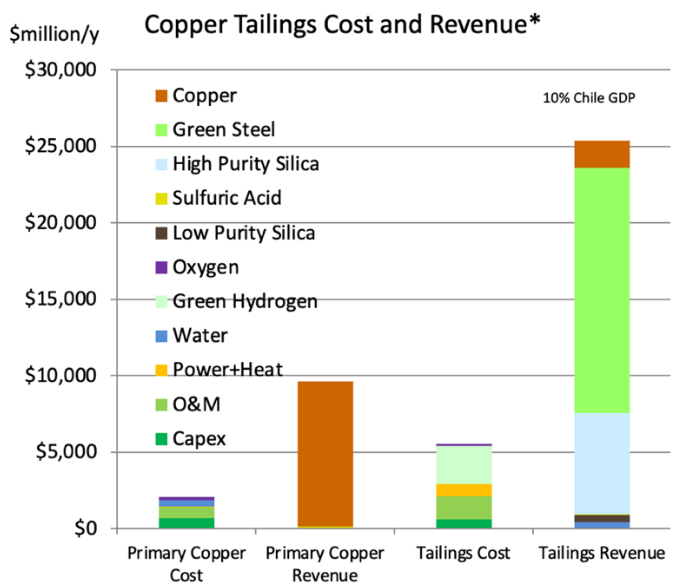


Figure 13 -- EWM Full Recovery Copper Tailings and Leachate Process™ Block Flow Diagram

In the Full Recovery Copper Tailings and Leachate Process,™ EWM Full Recovery Desalination® is used to desalinate seawater to provide industrial water for the primary copper recovery plant, high purity water for green hydrogen, and agricultural water for EWM Full Recovery Agriculture.™ In addition, it provides sodium hydroxide to CO2 capture (industrial source or DAC) to produce soda ash for green glass, chlorine to green PVC, and other minerals/fertilizers. The green glass, silicon, and PVC are used to produce PV modules domestically to provide the power required for the copper tailings refining process. The EWM Full Recovery Agriculture™ system provides biochar, CO2, biogas, and ethanol for glass, silicon, PVC, and Sustainable Aviation Fuel (SAF).

No waste brine or solids are produced – everything in the feed tailings and leachate is monetized as a high value commodity chemical or mineral. Essentially all chemicals are self-produced from effluent streams. Only silica (sand) is imported to meet the overall silica balance needs of the high value PV modules.

There is a high investment cost for the self-production of renewable power (including PV module raw materials and assembly), desalinated water, and Full Recovery Agriculture.™ However, this is a durable investment because these infrastructure investments can continue operation after the regional mines are depleted. Therefore, the high capital cost of the infrastructure investment (paid for by the full domestic monetization of the regional mineral resources) will be a useful, long lived regional asset.



*Based on 1 million tonnes/y copper production (Escondida Mine) excludes green H2 and O2 production (third party purchase)

Figure 14 -- EWM Full Recovery Copper Tailings and Leachate Process™ Sample Economics

The economics are for the waste leachate and tailings and exclude primary copper production (typically existing facilities at copper refineries). The Full Recovery Desalination® (seawater) is excluded which should have similar economics to the EWM Full Recovery Desalination® Seawater economics in Figure 2. Also excluded are the green glass, green silicon, green hydrogen, methanol, and PVC.

Significant renewable energy is to be used in the processing of the copper tailings, which can be supplemented with self-produced Electro-methanol or green H2 (E-methanol/green H2 - optional backup). EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources. This allows all the products to be green (CO2 emissions free, and fossil fuel free). Liquid hydrogen can be generated from green hydrogen as part of the LAES system, which provides cost competitive fuel for fuel cell, battery hybrid mining trucks and locomotives.

Cobalt

Approximately 50% of the global cobalt reserves and 70% of the global cobalt production are in the DRC (Investing News Network 2023). However, much of the cobalt is being mined under poor conditions (ABC News 2023). Therefore, high efficiency recovery of the remaining reserves (i.e., full recovery of nickel and copper with byproduct cobalt sulfate recovery as described in this paper) must be practiced as described below until these reserves can be accessed under acceptable conditions.

High purity cobalt sulfate is a critical ingredient in LIB cathodes. Cobalt provides stabilization between Nickel and Lithium. Zero and reduced cobalt chemistries are being researched due to the current unacceptable mining practices (Journal of Materials Chemistry A 2023). Compromising LIB chemistry, however, is undesirable because it causes compromised LIB battery performance and exacerbates the underlying cobalt mining poverty problem by decreasing ore market value.

The best option is to implement the EWM Full Recovery Cobalt Process™ together with the EWM Full Recovery Desalination® process in the cobalt producing region of the DRC. This region is a semi-arid region with a drought prone dry season (Jun-Nov) and a flood prone wet season (Dec-May). The significant cobalt ore produced in the region is exported as unrefined ore, severely limiting the revenue generated domestically within the mining region. China dominates global cobalt refining with over 80% of global cobalt refining capacity (USGS 2022). The DRC has trillions of dollars of mineral wealth especially cobalt, copper and nickel, but 98% of the DRC's mineral resources are exported unrefined and only 6% of the population has access to electricity and only 26% of the population has access to clean water (US International Trade Administration 2022).

EWM Full Recovery Cobalt Process™ combines imported sulfur with self-generated oxygen to generate sulfuric acid and SO2 required to digest (leach) and reduce the cobalt, nickel (if present), and manganese in the cobalt ore feed. The tailings are routed to secondary recovery and the primary leachate routed to minerals recovery, where the metals are separated by sequential precipitation. The sulfate from the leach solution is recovered from the lean leachate as sulfuric acid and used to produce high purity, battery grade cobalt sulfate, nickel sulfate, and manganese sulfate products.

The EWM Full Recovery Cobalt Tailings Process™ recovers all the minerals and water in the cobalt tailings slurry from the cobalt ore leaching step. The minerals are recovered as high volume, high value minerals, chemicals, and green raw materials, which provides the bulk of the revenue required to make the tailings recovery process economically profitable.

EWM Full Recovery Cobalt Process™

The EWM process consists of the following primary treatment steps:

- Digestion and minerals recovery
- Sulfuric acid and SO2 production
- Digestion and separation of cobalt ore (reducing conditions)
- Hydroxide sequential precipitation of metals
- Dissolving hydroxides in sulfuric acid and sulfate salt crystallization
- Recovery of sulfate as sulfuric acid

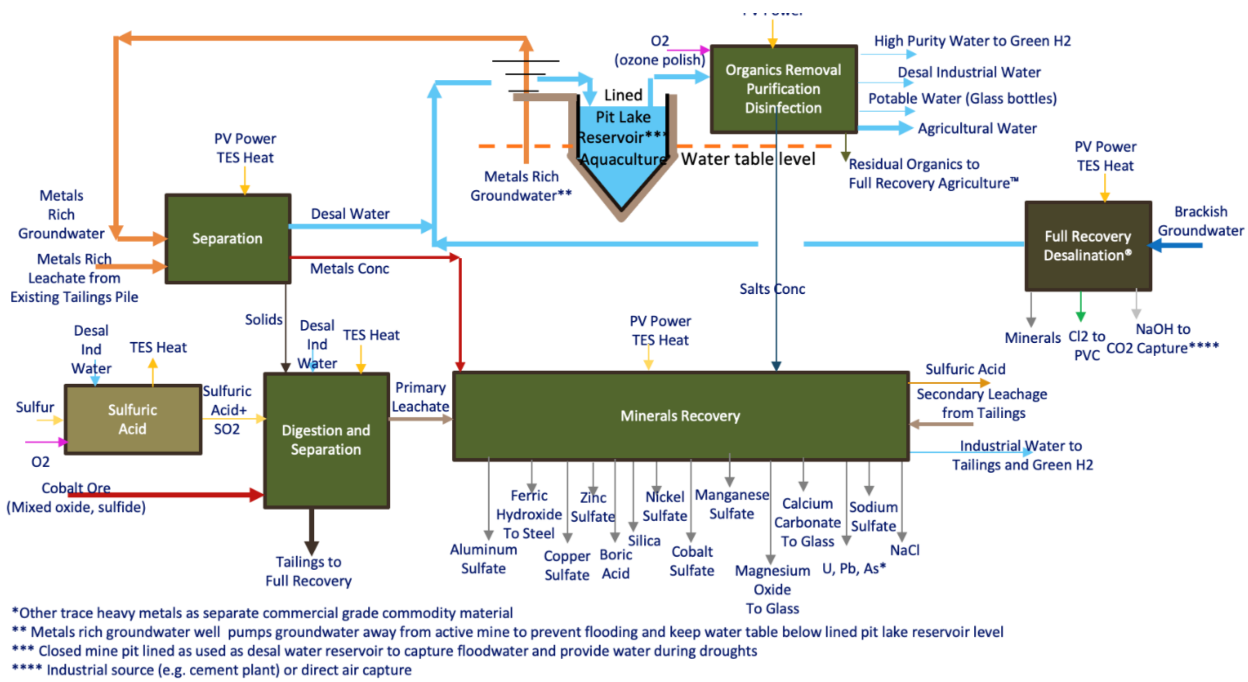


Figure 15 -- EWM Full Recovery Cobalt Process™ Block Flow Diagram for Primary Minerals Recovery

The EWM process for the tailings consists of the following tailings treatment steps:

- Separation of tailings from leachate
- Oxidative acidic leaching of tailings
- Minerals recovery from tailings leachate
- Green steel production
- Green glass production
- Green silicon production

- Green hydrogen production
- E-Methanol and green PVC production

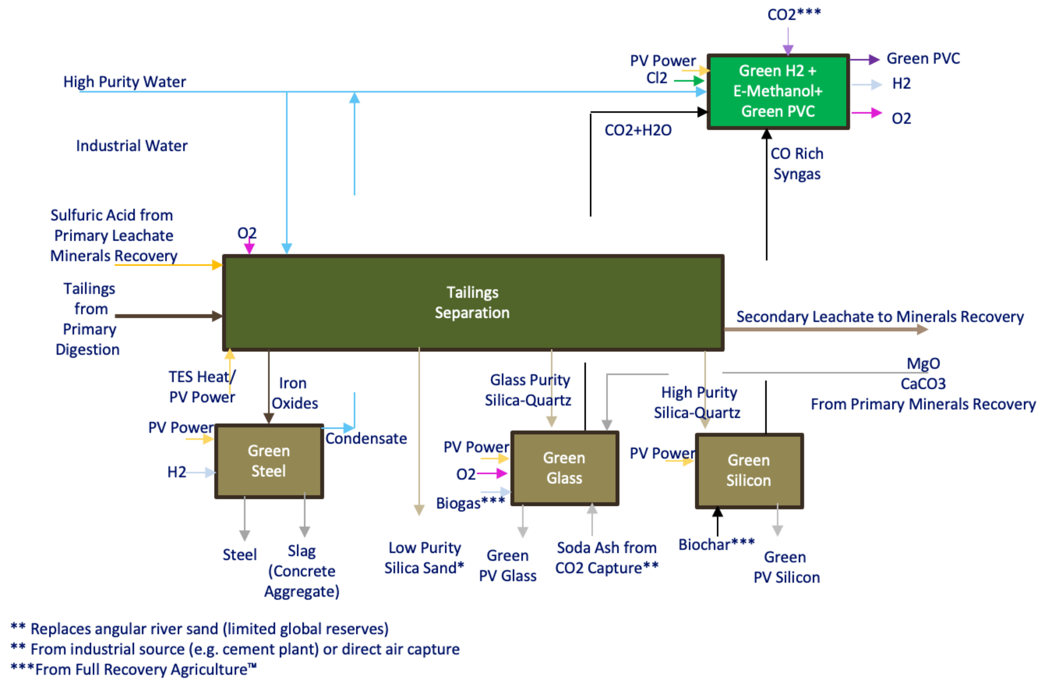


Figure 16 -- EWM Full Recovery Cobalt Process™ Block Flow Diagram for Tailings Minerals Recovery

Two desalination units are used in addition to cobalt ore processing. One is used to produce desalinated water from the metal rich groundwater near the mining operation. This prevents groundwater flooding of the pit mines during the rainy season and contamination of local groundwater with heavy metal leachate from the mines. The desalinated water is stored in lined legacy (ore depleted) pit mines. The desalinated water level is maintained above the groundwater table so that any leakage through the liner is from the reservoir to the groundwater. The concentrate from the minerals rich water desalination is sent to the mineral recovery section of the cobalt ore plant to increase product recovery.

The second desalination unit is used to desalinate deeper brackish groundwater to produce NaOH, chlorine, other minerals/fertilizers, and water for the EWM Full Recovery Agriculture™ system. The NaOH can be used in green glass production, and the chlorine used to make PVC. The green glass, silicon, and PVC are used to produce PV modules domestically to provide the power required for the refining process. EWM's optimized TES and LAES processes are designed to be used to meet the baseload power and heat requirements of the ore processing and refining units, as well as both desalination plants.

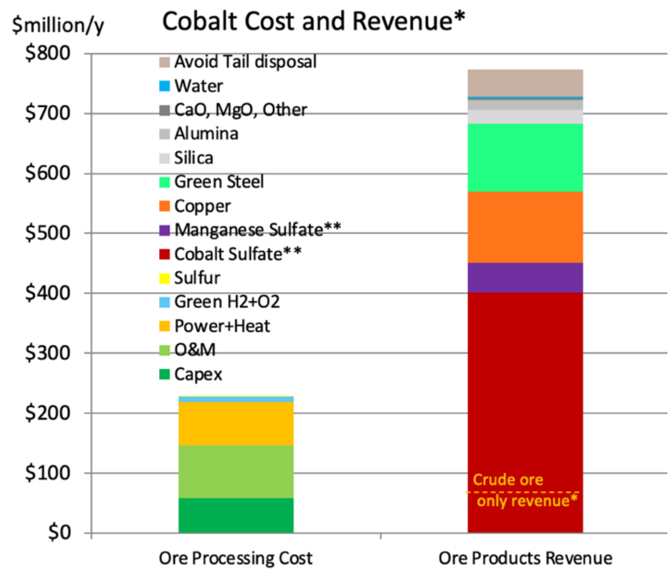
The stored desalinated water and the PV based power system also are used to support the local minemouth infrastructure requirements. This allows significant additional revenue and jobs, in addition to those from the high efficiency EWM Full Recovery Agriculture™ system, significantly improving the quality of life for the miners and supporting services workers.

All the equipment that EWM uses in its processes are commercially proven with performance guarantees from the various equipment suppliers.

The only input mineral required is low-cost solid sulfur, which is readily transported by truck or rail. Biochar is produced from crop residues and wood waste. Biochar can be cost effectively transported by truck or rail, similar to coal (the fossil fuel it replaces). All the carbon in the biochar and the feed tailings and leachate (carbonates) is captured and converted to PVC, which can be used in PV module construction (glass reinforced PVC for PV frames and supports).

All the cobalt, nickel, and manganese in the feed ultimately is converted to battery grade nickel sulfate, cobalt sulfate, and manganese sulfate. All the iron in the tailings is ultimately converted to green steel using onsite generated green hydrogen. All the silica, magnesium oxide, calcium oxide, and alumina in the tailings is converted to concrete aggregate (slag), and sand for concrete, green PV glass, or green solar grade silicon. The copper is captured as a high value metal.

No waste brine or solids are produced – everything in the feed tailings and leachate is monetized as a high value commodity chemical or mineral. Essentially all chemicals are self-produced from effluent streams. Only sulfur is imported to meet the overall sulfur balance needs of the high value sulfate products.



*Based on 13,000 tonnes/y contained cobalt in cobalt sulfate production (10% of DRC 2022 exported cobalt) excludes green H2 and O2 production (third party purchase)
** Battery grade
*** Onsite generation from high purity water
**** Estimated at 20% of battery grade revenue in 2% Co content crude ore (Extractive Industries and Society 2021)

Figure 17 -- EWM Full Recovery Cobalt™ Sample Economics

The economics include sulfuric acid production for onsite use, including all the primary minerals and the tailings mineral recovery. The Full Recovery Desalination® (brackish groundwater and metals rich groundwater) is excluded, which should have similar or better economics to the EWM Full Recovery Desalination® Seawater economics in Figure 2. Also excluded are economics from green glass, green silicon, green hydrogen, methanol, and PVC.

There is a high investment cost for the self-production of renewable power (including PV module raw materials and assembly), desalinated water, and Full Recovery Agriculture.™ This, however, is a durable investment because these infrastructure investments can continue operation after the regional mines are depleted. Therefore, the high capital cost of the infrastructure investment (paid for by the full domestic monetization of the regional mineral resources) will be a useful, long lived regional asset.

Significant renewable energy is to be used in the processing of the cobalt, which can be supplemented with self-produced Electro-methanol or green H2 (E-methanol/green H2 - optional backup). EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources. This allows all the products to be green (CO2 emissions free, and fossil fuel free). Liquid hydrogen can be generated from green hydrogen as part of the LAES system, which provides cost competitive fuel for fuel cell, battery hybrid mining trucks and locomotives.

Iron/Steel

China produces approximately 70% of the global primary (non-scrap or recycle based) steel (Sustainability 2021). China uses coal-based blast furnace technology to produce 90% of its steel and emits 2.5 tonnes of CO2 per tonne steel (Cleveland Cliffs 2021). Using steel produced from coal is not consistent with the energy transition goal of eliminating fossil fuel CO2 emissions.

Significant primary steel and zinc (see Zinc above) would be required for the energy transition for supports (PV solar farms, wind farms, and transmission towers) if the current practice of using galvanized steel is used for these supports. Eventually, the steel would be recycled, but primary steel would be required to provide the large growth required for the energy transition.

As discussed in the Zinc section above, a better materials option for the supports required by the energy transition is a composite PVC-glass fiber with a limited amount of encapsulated primary steel. Green primary steel should be used in order to eliminate the CO2 emissions from the limited primary steel required. Primary green steel production is a byproduct of most of EWM's full recovery mining and tailings processes (Copper, Cobalt, Manganese, and Alumina), because most of the waste tailings contain significant amounts of unused iron oxide. These EWM full recovery processes eliminate primary steel CO2 emissions and reduce demand for mined iron oxide ore for the primary steel required to support the energy transition.

Glass fiber reinforced PVC is a major product from EWM's Full Recovery Desalination® process and is produced from seawater and captured CO2. A tonne of CO2 is sequestered in the PVC per tonne of PVC. Therefore, a PVC-glass composite based support solution for the green energy transition would be sequestering significant CO2 instead of emitting it. The PVC-glass fiber thermoplastic composite materials used for window frames are designed to be disassembled and remelted to achieve 100% recyclability (Rehau 2022).

Manganese

Approximately 30% of the global manganese reserves and 35% of global manganese production are in the Kalahari basin of South Africa (Kalahari desert); and approximately 15% of global manganese reserves and 15% of global manganese production are in northern and western Australia (Investing News Network 2023). Both of these regions are arid with excellent solar resources.

Most manganese ore is used in steel production, but approximately 10% is converted to high purity manganese sulfate for LIB electrodes. Currently, China produces 90% of the battery grade manganese and manganese sulfate. Consumption of battery grade material is expected to grow at a significant rate (28% CAGR) due to growth in NCM LIBs (S&P Global 2023).

Manganese ore prices are low, currently below $5/tonne delivered to China (USGS 2023). The price of high purity, battery grade, manganese sulfate, however, is significantly higher - $2,400/tonne and expected to increase to $5,000/tonne due to China's large market share (90%) on high purity, battery grade manganese sulfate and increasing demand for NMC based EV and grid batteries (S&P Global 2023).

To provide additional domestic revenue to the ore producers (e.g., South Africa and Australia) the EWM Full Recovery Manganese Process™ should be used at the deep-water loading port to convert a portion of the highest purity ore to battery grade manganese sulfate.

The EWM Full Recovery Manganese Process™ roasts the manganese ore with low-cost imported sulfur and self-generated oxygen at temperatures above the boiling point of sulfur (445^0 C) to generate SO2, CO2, and reduced ore. The reduced ore, SO2, and CO2 are routed to ore leaching and minerals recovery. In the mineral recovery section, the metals are separated by sequential precipitation. Sulfate is recovered from the lean leachate as sulfuric acid and used to produce high purity, battery grade manganese sulfate. Silica (quartz), iron oxide, magnesium oxide, and calcium carbonate products are also recovered. The silica, magnesium oxide, calcium carbonate, and sodium hydroxide (from seawater desalination – see below) are converted to green glass. The iron oxide is converted to green steel.

The EWM Full Recovery Manganese Process™ recovers all the minerals and water in the manganese ore. The minerals are recovered as high volume, high value minerals, chemicals and green raw materials, which provides the bulk of the revenue required to make the overall recovery process economically profitable.

EWM Full Recovery Manganese Process™

The EWM process consists of the following treatment steps:

- Ore roasting with sulfur to produce SO2, CO2, and reduced ore
- Digestion and separation of manganese ore
- Hydroxide sequential precipitation of metals
- Dissolving manganese hydroxide in sulfuric acid and sulfate salt crystallization
- Recovery of sulfate as sulfuric acid
- Crystallization of potassium sulfate

- Green glass production
- Green steel production
- Green hydrogen, E-Methanol, and green PVC production

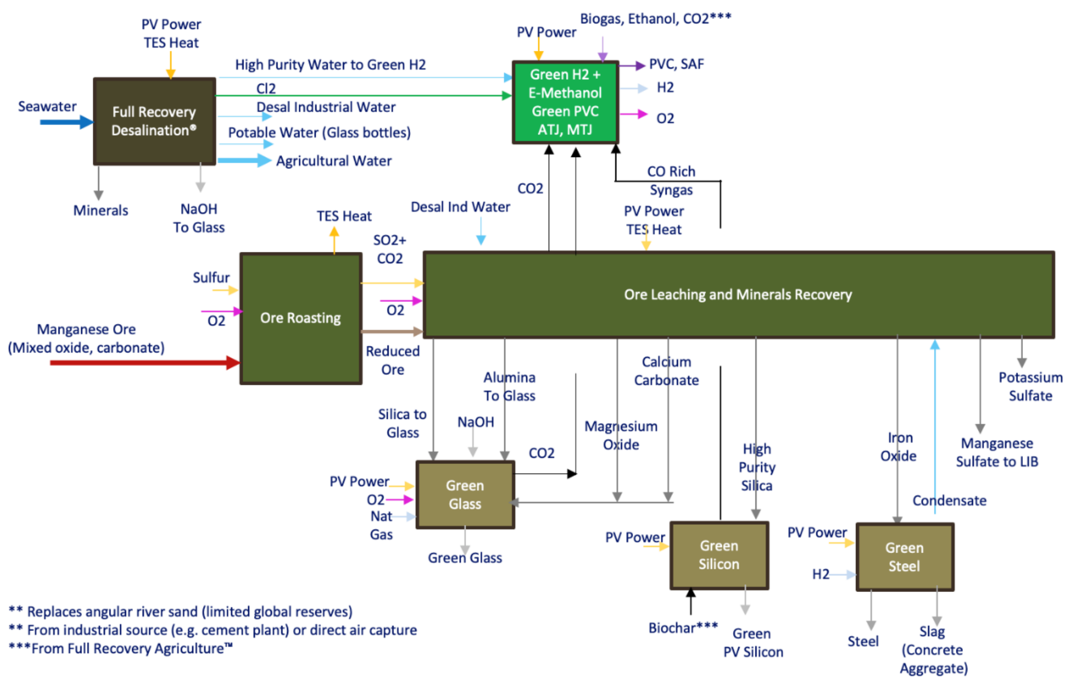
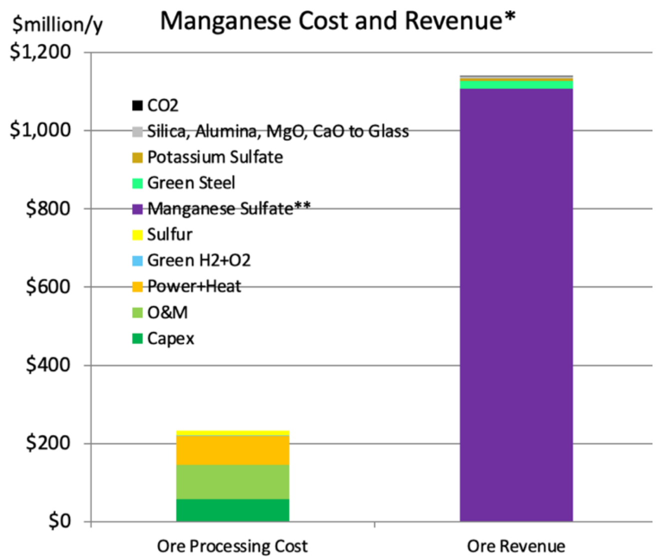


Figure 18 -- EWM Full Recovery Manganese Process™ Block Flow Diagram

An EWM Full Recovery Desalination® unit is used to desalinate seawater to provide industrial water for the manganese processing plant, high purity water for green hydrogen, and agricultural water for EWM Full Recovery Agriculture.™ In addition, it provides sodium hydroxide to green glass, chlorine to green PVC, and other minerals/fertilizers. The green glass, silicon, and PVC can be used to produce PV modules domestically to provide the power required for the refining process. The EWM Full Recovery Agriculture™ system provides biochar, CO2, biogas, and ethanol for glass, silicon, PVC, and Sustainable Aviation Fuel (SAF).

No waste brine or solids are produced – everything in the feed ore is monetized as a high value commodity chemical or mineral. Essentially all chemicals are self-produced from effluent streams. Only sulfur and silica (sand) are imported to meet the overall sulfur and silica balance needs of the high value sulfates and PV products.



*Based on 120,000 tonnes/y contained manganese in manganese sulfate production (10% of 2030 battery market) excludes green H2 and O2 production (third party purchase)
** Battery grade
*** Onsite generation from high purity water

Figure 19 -- EWM Full Recovery Manganese™ Sample Economics

The economics include ore roasting and leaching, minerals recovery, and green steel. The Full Recovery Desalination® (seawater) is excluded, which should have similar or better economics to the EWM Full Recovery Desalination® Seawater economics in Figure 2. Also excluded are green glass, green silicon, green hydrogen, methanol, and PVC economics.

There is a high investment cost for the manganese refining, self-production of renewable power (including PV module raw materials and assembly), desalinated water, and Full Recovery Agriculture.™ This, however, is a durable investment because these infrastructure investments can continue operation after the regional mines are depleted using imported manganese ore. Therefore, the high capital cost of the infrastructure investment (paid for by the full domestic monetization of the regional mineral resources) will be a useful, long lived regional asset.

Significant renewable energy can be used in the processing of the manganese, which can be supplemented with self-produced Electro-methanol or green H2 (E-methanol/green H2 - optional backup). EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources. This allows all the products to be green (CO2 emissions free, and fossil fuel free). Liquid hydrogen can be generated from green hydrogen as part of the LAES system, which provides cost competitive fuel for fuel cell, battery hybrid mining trucks, and locomotives.

Aluminum

Australia is the largest producer of bauxite (aluminum ore material) and has the second largest amount of bauxite reserves. Australia also has the second largest refined bauxite (alumina - aluminum intermediate) production. Guinea has the largest bauxite reserves and is the second largest bauxite producer. Guinea has minimal bauxite refining. China has 15% of Australia's bauxite reserves, 90% of Australia's bauxite production, and 230% of Australia's alumina production. China is by far the global leader in alumina production and produces the majority of the world's aluminum based on high carbon footprint coal fired power plants and fossil fuel based expendable graphite electrodes. (Sustainability 2021, Alcoa 2022).

Aluminum from China typically emits 15 tons of CO2 per tonne of aluminum (Alcoa 2022). Elysis, a joint venture formed by Alcoa and Rio Tinto, is currently commercializing an inert electrode aluminum process that eliminates CO2 emissions from the electrodes (Light Metal Age 2022). There, however, is still a large power requirement (13-15 MWh/tonne) to convert alumina to aluminum and there is also 1 tonne CO2/tonne aluminum emission from bauxite to alumina production, which requires high temperature (> 1200 C) calcining (German government Federal Institute for Geosciences and Natural Resources 2020).

Alumina production from bauxite ore produces a large tailings stream. Approximately 2-3 tonnes of tailings (dry solids basis) are produced per tonne of aluminum. The tailings contain residual sodium hydroxide (approximately 0.1 tonnes/tonne tailings solids) and heavy metals and are typically a 50% water thickened sludge stored in an earthen walled containment system. (All above sourced from German government Federal Institute for Geosciences and Natural Resources 2020). The tailings represent a significant waste disposal issue due to potential for loss of containment during flood events. In addition, the tailings contain valuable minerals that are not monetized.

In the green energy transition, aluminum currently is used as both an electrical conductor in new transmission lines and as a lightweight alloy for structural components, including PV frames and EV components. Composite polymer materials (e.g., glass fiber reinforced PVC thermoplastic) are replacing double and triple pane aluminum window frames and have approximately the same strength to weight ratio as aluminum. The frame design and PVC/glass fiber thermoplastic composite material are design to be remelted to achieve 100% recyclability. Internal untreated steel (encapsulated by corrosion-proof PVC) also can be used to increase frame strength for very large multi-pane windows. (Rehau 2022)

Green PVC can be produced from captured CO2 and green hydrogen using methanol as an intermediate. China has commercialized the production of ethylene from coal-based methanol, and currently the largest global use of methanol is for ethylene and propylene production (HIS Markit 2018, Methanol Institute 2021). Green PVC captures approximately 1 tonne of CO2/tonne

PVC. PVC based glass fiber composites are the lowest cost polymer composites because PVC contains approximately 60% chloride produced from low-cost salt.

Aluminum also can be alloyed with magnesium, silicon, and copper to produce a stronger, more conductive material (General Cable Technologies Corp 2020). This reduces both aluminum requirements and structural support requirements (i.e., number of transmission towers).

For the green energy transition, the following will minimize aluminum resource requirements, energy consumption, and CO2 emissions:

- Substitute PVC/glass/steel composites for PV frames and supports for aluminum
- Substitute PVC/glass/steel composites for EV components for aluminum
- Use aluminum alloyed with green magnesium, silicon, and copper in electrical conductor service
- Substitute higher strength to weight ratio green magnesium-aluminum alloys for pure aluminum in applications wherein PVC/glass/steel composites are not suitable (i.e., aviation, higher temperatures services)

In addition, the EWM Full Recovery Bauxite Tailings Process™ should be used to monetize the waste tailings. The waste bauxite tailings contain several valuable components including (Sustainability 2021):

- Iron oxide (suitable for green steel production)
- Silica (suitable for glass, and concrete production)
- Titanium dioxide (paints, coating, plastic additive for UV protection)
- Rare earth elements
- Residual alumina
- Residual sodium hydroxide
- Water

The revenue from the refined tailings can exceed the revenue for the extracted alumina due to the high market values for the refined components in the tailings and the large ratio of tailings to alumina. In addition, fully monetizing the tailings minimizes disposal environmental costs and mining requirements to produce the materials recovered from the tailings.

Tailings from bauxite refining are separated in a multistage hydrometallurgical process. Aluminum hydroxide is recovered and recycled to the alumina plant. The residual caustic is converted into soda ash using CO2 removed from the aluminum hydroxide to alumina calciner exhaust gas, eliminating approximately half of its CO2 emissions. The resulting soda ash, recovered silica, magnesia, and calcium carbonate are used to produce green solar glass for PV modules. Iron oxide is recovered and converted to green steel using green hydrogen produced from a portion of the recovered water. Titanium is recovered as an industrial purity commodity mineral. A small amount of rare earths are recovered as a concentrate for further processing in a larger scale facility.

The EWM Full Recovery Bauxite Tailings Process™ recovers all the minerals and water in the bauxite tailings. The minerals are recovered as high volume, high value minerals, chemicals and green raw materials, which provides the bulk of the revenue required to make the overall recovery process economically profitable.

EWM Full Recovery Bauxite Tailings Process™

The EWM process consists of the following treatment steps:

- Multistage leaching
- Separation of dissolved alumina and caustic
- Conversion of caustic to soda ash with captured CO2
- Minerals recovery from tailings leachate
- Green steel production
- Green glass production
- Green hydrogen production
- E-Methanol and green PVC production

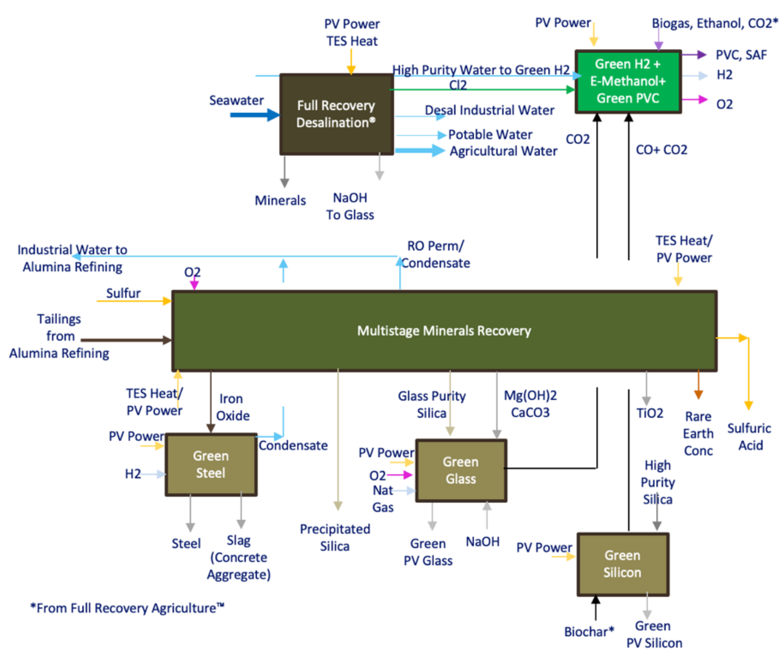


Figure 20 -- EWM Full Recovery Alumina Tailings Process™ Block Flow Diagram

An EWM Full Recovery Desalination® unit is used to desalinate seawater to provide industrial water for the bauxite processing plant, high purity water for green hydrogen, and agricultural water for EWM Full Recovery Agriculture.™ In addition, it provides sodium hydroxide to green glass, chlorine to green PVC, and other minerals/fertilizers. The green glass, silicon, and PVC are used to produce PV modules domestically to provide the power required for the refining process. The EWM Full Recovery Agriculture™ system provides biochar, CO2, biogas, and ethanol for glass, silicon, PVC, and Sustainable Aviation Fuel (SAF).

Ultimately, green aluminum-magnesium-silicon-copper alloys could be produced onsite from the alumina, magnesium, and silicon produced onsite with a small amount of imported copper. The energy intensive aluminum alloy production process would use low-cost, self-produced PV power with EWM's optimized TES and LAES process to economically convert the intermittent PV power to baseload power.

No waste brine or solids are produced – everything in the feed tailings and contained leachate is monetized as a high value commodity chemical, mineral, or concentrate (rare earths). Essentially all chemicals are self-produced from effluent streams. Only sulfur is imported and converted to export sulfuric acid (value upgrade).

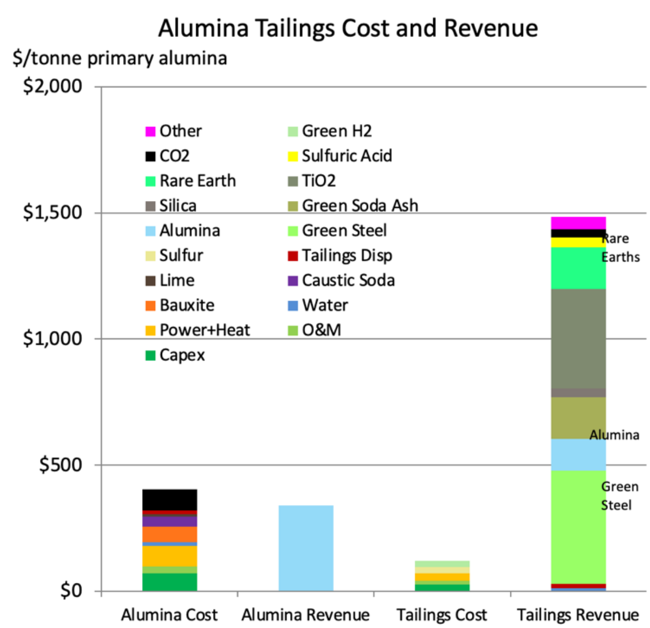


Figure 21 -- EWM Full Recovery Alumina Tailings™ Sample Economics

The economics are for the multistage mineral recovery. The Full Recovery Desalination® (seawater) is excluded, which should have similar economics to the EWM Full Recovery

Desalination® Seawater economics in Figure 2. Also excluded are the green glass, green silicon, and green hydrogen, methanol, and PVC economics.

There is a high investment cost for the bauxite refining, self-production of renewable power (including PV module raw materials and assembly) and desalinated water. This, however, is a durable investment because these infrastructure investments can continue operation after the regional mines are depleted using imported bauxite ore. Therefore, the high capital cost of the infrastructure investment (paid for by the full domestic monetization of the regional mineral resources) will be a useful, long lived regional asset.

Significant renewable energy is to be used in the processing of the bauxite tailings, which can be supplemented with self-produced Electro-methanol or green H2 (E-methanol/green H2 - optional backup). EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources. This allows all the products to be green (CO2 emissions free, and fossil fuel free). Liquid hydrogen can be generated from green hydrogen as part of the LAES system, which provides cost competitive fuel for fuel cell, battery hybrid mining trucks, and locomotives.

Neodymium

Neodymium is an important Rare Earth Element (REE) used for Electric Vehicle (EV) and offshore wind turbine magnets. Neodymium has unique chemical and physical properties that optimize the performance of the high efficiency permanent magnet motors and generators used in EV's and offshore wind turbines.

The demand for neodymium could greatly surpass the anticipated supply in the near future (EU Joint Research Center 2020). Although there will likely be enough neodymium in the world to satisfy offshore wind demand, there is concern that turbine makers will end up competing with the electric vehicle market (Nature Sustainability 2019).

China refines approximately 70% of the global REE's, including Neodymium. China's current REE refining processes cause land and water contamination (tailings and spent chemical effluents), which cause the refined Chinese Neodymium to be considered an environmental and supply risk. (S&P Global 2023).

South Africa's Steenkampskraal Mine is currently being reactivated as a Neodymium rich REE mine. It has one of highest grades of rare earth elements in the world. It contains 15 elements and 86,900 tons of total rare earth oxides, with one of the largest deposits of neodymium and praseodymium globally. The nearby Zandkopsdrift Mine has successfully completed an initial feasibility study and has a 2027 target to commence commercial production. The mines are in an arid region of northwest South Africa, 80-90 km from the Atlantic Ocean. Both of these sites have significant available land for additional REE ore mining expansion. (Steenkampskraal Monazite Mine Pty, Ltd 2023, Brookings Institute 2023, NS Energy 2023, Frontier Rare Earths 2023). A similar REE mining project (Lofdal Heavy Rare Earths Project) is under development in Namibia at a site in the same arid region, approximately 100 km from the Atlantic ocean (NS Energy 2023). These REE mining sites are located in an arid, largely undeveloped region, and should be suitable for large, utility scale PV solar farms.

Ideally these mining sites or a common refining facility could be used to refine the raw ore and to recycle used neodymium magnets. Advanced hydrometallurgy processes using multi-step leaching precipitation and solvent extraction can effectively recover high purity neodymium from both ore and recycle magnets. The application of this technology, however, is limited by its high water and chemicals consumption (Sustainable Chemistry 2021).

EWM is developing a modified version of its full recovery hydrometallurgical processes to recover and refine the neodymium and other rare earth elements. As with EWM's other processes, the chemicals (acids and alkalis) will be recovered and recycled using the low-cost PV resource available at the mine and refinery site together with its optimized TES and LAES energy storage system.

A seawater based Full Recovery Desalination® plant would be included to provide the makeup chemicals and increased water supply. This avoids depleting the limited supply of local groundwater currently planned for the Steenkampskraal mining operations and replaces the conventional low recovery (50 %) seawater desalination planned for the Zandkopsdrift mining operations. The additional water supply also would allow EWM's Full Recovery Agriculture™ to be co-located near the mining area to take advantage of the mine infrastructure (road and rail) and fully harvest the world class solar resource and large tracts of available land.

Co-location of the neodymium magnet recycling facility at the neodymium rich REE ore refining site maximizes the value of the capital-intensive refinery. Initially most of the feedstock will be freshly mined REE ore concentrate. As EV's and wind turbines become prevalent, the refinery output remains the same, but the feedstock changes to an even greater percentage of recycled feedstock instead of freshly mined REE concentrate. The downstream magnet plants have the freedom to optimize magnet formulation and feed material purity requirements. The magnet plants' feedstock logistics and permitting and discharge byproducts remain the same, independent of fresh REE ore concentrate feed or recycled magnet feed.

Rare earth concentrates from EWM's Full Recovery Alumina Tailings Process™ also can be fed to the neodymium refinery as a minor supplemental feed. This would provide a larger scale, more cost-effective way to recover the neodymium and other rare earths contained in the alumina tailings.

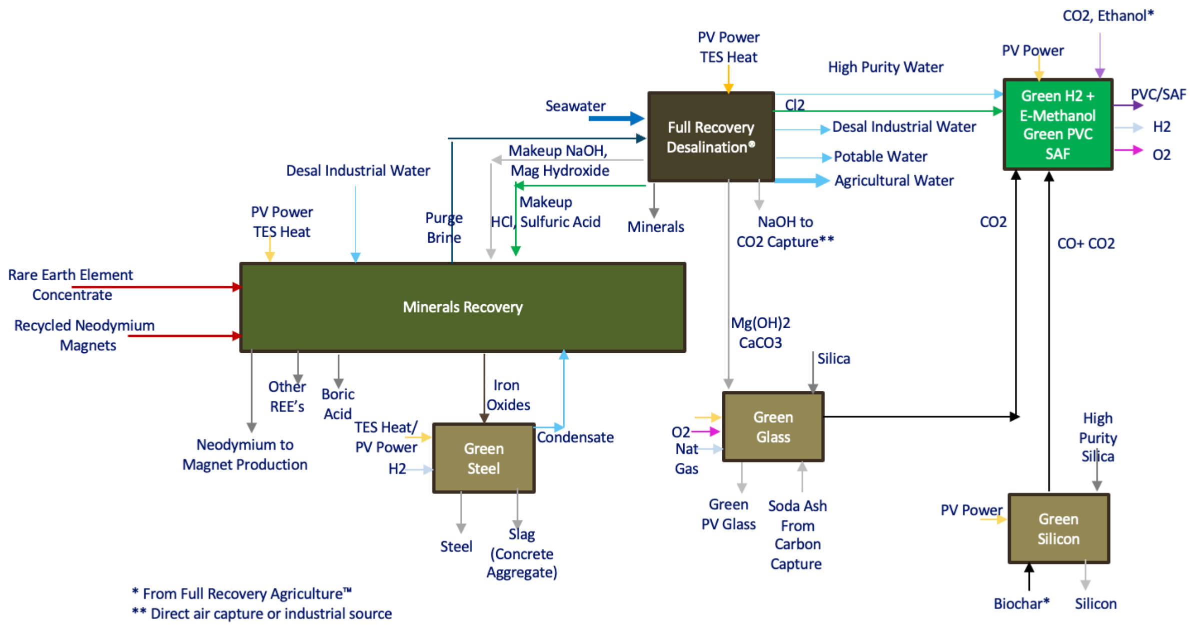


Figure 22 -- EWM Full Recovery Neodymium Process™ Block Flow Diagram

An EWM Full Recovery Desalination® unit is used to desalinate seawater to provide industrial water for the neodymium processing plant, high purity water for green hydrogen, and agricultural water for EWM Full Recovery Agriculture.™ In addition, it provides sodium hydroxide to CO2 capture (industrial source or DAC) to produce soda ash for green glass, chlorine to green PVC, and other minerals/fertilizers. The green glass, silicon, and PVC are used to produce PV modules domestically to provide the power required for the refining process. The EWM Full Recovery Agriculture™ system provides biochar, CO2, biogas, and ethanol for glass, silicon, PVC, and Sustainable Aviation Fuel (SAF).

No waste brine or solids are produced – everything in the feed concentrate and recycled magnets is monetized as a high value commodity chemical or mineral. Essentially all chemicals are self-produced from effluent streams. Only silica (sand) is imported to meet the overall silica balance needs of the solar glass and silicon for PV self-production.

There is a high investment cost for the Neodymium refining and recycling, self-production of renewable power (including PV module raw materials and assembly), production of desalinated water, and Full Recovery Agriculture.™ This, however, is a durable investment because these infrastructure investments can continue operation after the regional REE mines are depleted using imported recycled Neodymium magnets. Therefore, the high capital cost of the infrastructure investment (paid for by the full domestic monetization of the regional REE mineral resources) will be a useful, long lived regional asset.

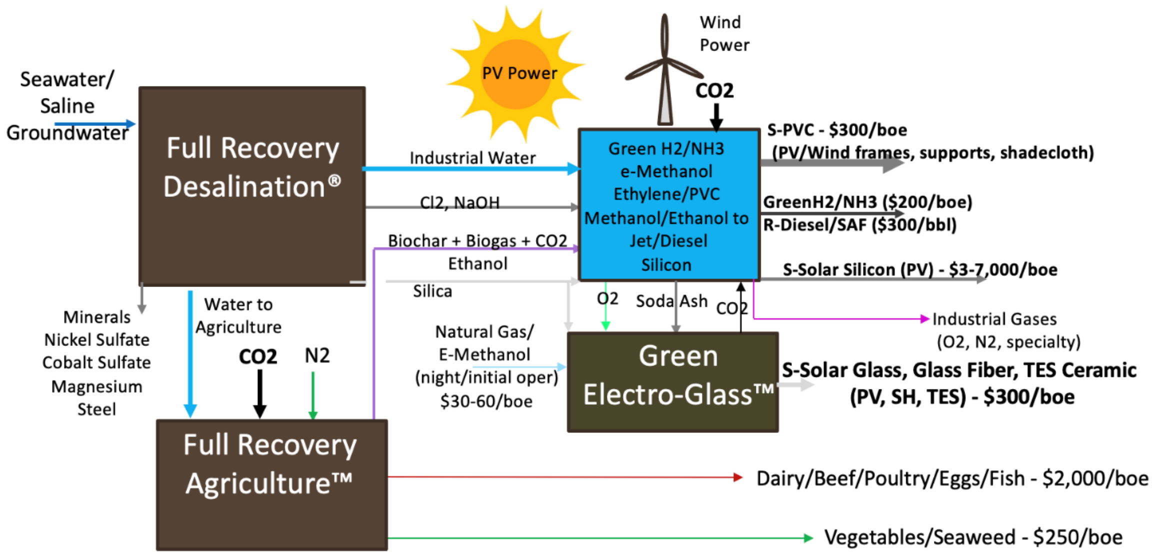
International investors are developing green hydrogen projects in both South Africa and Namibia to monetize the excellent regional solar resource and land availability (Energy Capital and Power 2023). Combining additional green hydrogen production for export as liquid hydrogen or hydrogen derivatives (ammonia, SAF, and E-Methanol) with the REE mining opportunity could allow significant infrastructure savings and the common use of a larger scale, seawater fed Full Recovery Desalination® plant.

Mining, refining, and recycling of the Neodymium can be done with renewable energy, which can be supplemented with self-produced Electro-methanol or green H2 (E-methanol/green H2 - optional backup). EWM has developed customized Thermal Energy Storage (TES) and Liquid Air Energy Storage (LAES) to cost effectively allow 100% renewable energy supply from onsite or local power sources. This allows all the products to be green (CO2 emissions free and fossil fuel free). Liquid hydrogen can be generated as part of the LAES system, which provides cost competitive fuel for fuel cell, battery hybrid mining trucks, and locomotives.

Non-Metals

Non-metals required for the green energy transition are:

- Graphite
- Phosphorous/Phosphate
- Polymers
- Glass
- Silicon
- Concrete



EWM's Full Recovery Desalination®, Full Recovery Agriculture®, Green Electro-Glass®, processes produce green high demand products and food.

Figure 23 --Depicts Materials Generated Based on Net Capture of Direct Air Captured CO2, or CO2 Captured from Industrial Sources (i.e., Cement for Concrete)

The EWM Full Recovery Agriculture™ process is used to produce the following:

- Biochar for green graphite production
- Phosphate fertilizers

These will be discussed in a future Full Recovery Agriculture™ process EWM paper.

Polymers

As discussed above, PVC glass fiber composites are a potential major product from EWM's Full Recovery Desalination® process. PVC is a preferred polymer because it has the following benefits versus other polymers:

- Lowest cost since approximately 60% of PVC is based on low-cost salt instead of high-cost hydrocarbons
- Multiple forms (glass fiber reinforced and foamed) are used for a wide range of applications (piping and building materials – flooring, siding, roofing, and interior paneling)
- Recyclable thermoplastic (requires recyclable product designs and fabrication systems)
- Green production path using seawater and captured CO2 (unlimited feedstocks)

- High strength to weight ratio (equivalent to aluminum, 2 times steel)

In addition to PVC glass fiber composites for structural use, PVC based membranes are being developed for Proton Exchange Membranes (PEM) used for electrolysis based green hydrogen production (Hydrogen Energy 2023, Membranes 2022). The PVC based membranes could replace fluorocarbon-based membranes currently used for PEM based green hydrogen.

The production of the fluorocarbon-based membranes has been associated with emissions of Polyfluoralkyl Substances (PFAS), which are facing environmental scrutiny (Time 2023). PVC is much cheaper than the fluorocarbon material due to the lower cost of chloride versus fluoride raw materials (chlorine versus hydrogen fluoride) and lower cost of production. The PVC based PEM membranes under development are being designed to operate at higher temperatures (100-140 C vs 70-80 C) than the existing fluorocarbon-based PEM membranes. The higher temperature increases conductivity and electrolysis performance and allows more efficient use of the significant (25% of input power) byproduct heat in the EWM TES system.

EWM Green Glass Process™

As shown in the block flow diagram (Figure 23), EWM has developed an EWM Green Glass Process™ to integrate with its Full Recovery Desalination® process. This process has a net capture of CO2, turning a typically difficult to decarbonize process into a carbon capture process.

The two main feedstocks of glass are quartz (silica) and soda ash. Quartz is a byproduct of several of EWM's full recovery mining processes (copper, cobalt, alumina, and manganese). In addition, quartz-based sand is an abundant mineral. If necessary, iron contamination of lower purity silica (below current glass grade) can be acid leached using the optional HCl byproduct from the EWM Full Recovery Desalination® process. This produces higher purity silica and a ferric chloride byproduct.

Green sodium hydroxide is a major product of EWM's Full Recovery Desalination® process. The sodium hydroxide is used to capture the CO2 from industrial sources (e.g., alumina/lime calciners and cement plants) or from direct air capture to produce soda ash required for glass production. This eliminates the need to produce mined or synthetic soda ash that is based on mining fossilized carbonate or bicarbonate minerals (limestone or trona feedstocks), which currently use fossil fueled calciners. This avoids approximately 1 tonne of CO2 emissions per tonne soda ash (Solvay 2019), and any additional CO2 from soda ash transportation. In contrast, EWM's green soda ash captures approximately 0.5 tonnes of CO2 per tonne soda ash.

A small amount of magnesia and calcium carbonate also is required. These can be supplied by EWM's full recovery mining or desalination process. Alternatively, mined dolomite (calcium magnesium carbonate) can be used because the EWM Green Glass Process™ mines the carbonates to create CO2 that is captured as carbon in the PVC.

Significant PV power, supplemental fuel (natural gas, biogas, and E-Methanol), and oxygen are required by the glass kiln to produce glass. Oxyfuel/power hybrid kilns (current state-of-the-art) produce glass and a concentrated CO2 effluent that can be used in E-methanol and PVC production.

Silicon

China produces approximately 90% of the solar grade polysilicon used in PV modules (PV Magazine 2023). China uses low-cost coal for silica reduction and for power generation to be used by electric arc furnaces and energy intensive silicon purification. Coal based, high purity PV grade silicon production emits 141 tonnes of CO2 per tonne of silicon and approximately 25% of the life of the PV module is required to offset the CO2 emissions from the Chinese coal-based silicon (HPQ Silicon, Canadian Solar 2021).

The EWM Full Recovery Silicon™ process uses biochar (carbon from biological direct air capture) from the EWM Full Recovery Agriculture™ system and PV based power in conjunction with the optimized TES and LAES system developed for desalination to produce green silicon. EWM's process recovers the CO and CO2 rich offgas from silicon production and converts it to PVC for PV frames and supports. Therefore, EWM is able to capture and sequester 17 tonnes of CO2 per tonne of silicon.

High purity quartz (>99.5% SiO2), which is a limited resource, is typically required for silicon production. The EWM Full Recovery Silicon Process™ can use lower purity quartz (silica) with a higher iron impurity level. This silica resource is much more abundant and can be acid leached using the optional HCl or chlorine byproduct from the EWM Full Recovery Desalination® process. This produces higher purity silica and a ferric chloride byproduct. In addition, a new silicon carbothermic smelting method has been successfully piloted that removes impurities using chlorine during silica reduction to silicon. The process is currently being commercialized with an initial commercial plant startup of 2026 (Pyrogenesis Canada 2017, HPQ Silicon 2023).

Silicon production is best located in arid areas with a high solar resource so that PV power can supply renewable energy to support the power intensive production of solar grade silicon. PV panel production also can occur at this location. This allows both the supply of PV panels and the demand for PV power to be co-located in the solar resource region. This minimizes material and energy transportation requirements and allows the regional economy to benefit from fully monetizing its solar resource.

EWM's Full Recovery Desalination® process facilitates this model by providing low-cost water (seawater or brackish groundwater based) and PV module feedstocks (PVC, glass, and silicon) to these arid locations. EWM has also developed an add on to the EWM Full Recovery Desalination® process to harvest periodic excess stormwater in conjunction with brackish groundwater based Full Recovery Desalination.® This can significantly extend the brackish groundwater resource to support larger scale, longer term PV module production.

Concrete

Concrete currently is used in the energy transition for foundations for PV pilings, wind turbines, and transmission line support towers. Increasing global demand for sand and gravel is leading to social, environmental, and political issues that are becoming more widely recognized. Desert sand is not suitable because it is typically too fine grained and smooth for concrete production, which requires angular sand (typically river or lake sand) (Resources 2022). Concrete also contains cement and steel and results in approximately 0.1 tonnes CO_2 emissions per tonne installed cement foundation (Mineral Products Association 2022). A large reinforced concrete footing for a wind turbine has a typical weight of 1500 tonnes, which requires multiple truckloads of wet cement from a regional cement plant (additional CO_2 emissions).

A cost competitive alternative to concrete is PVC-glass composite internal steel reinforced micropiles. Micropiles resist both vertical compression and uplift forces. The weight of the PV panels, wind turbines, and transmission lines causes compression forces on the micropiles. The overturning of PV panels, power-transmission, or wind turbine towers due to wind causes uplift forces. Micropiles have a significant mechanical advantage for these energy transition services versus traditional large concrete foundations, which must be massive enough to resist both compression and worst-case windstorm overturning forces (Shandong Electric Power Engineering Consulting Institute 2016).

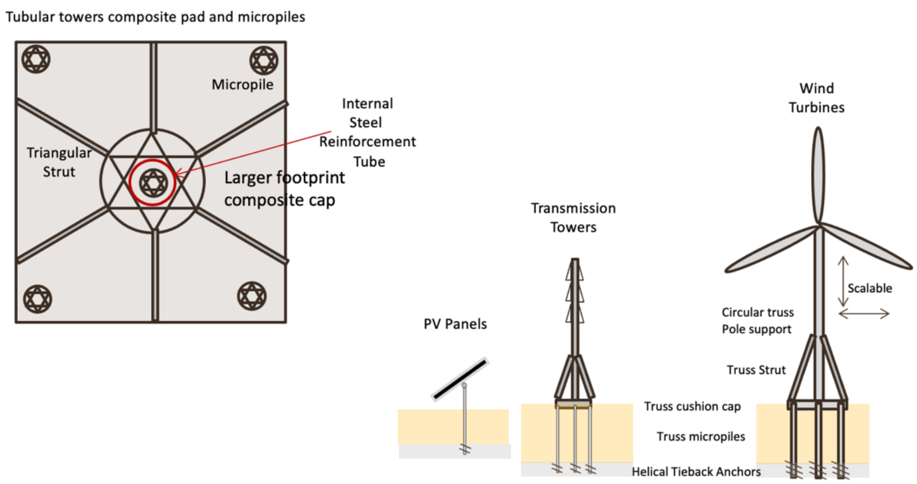


Figure 24 -- Conceptual Design of a PVC-glass Internal Steel Composite Based Micropile Foundation System is Shown for the Energy Transition Services (PV foundation, Transmission Line Foundation, and Wind Turbine Foundation)

The concept is similar to a tree root system that supports tree/shrub like structures (PV panels, wind turbines, and transmission lines). The micropile system uses a broader and deeper system of hollow micropiles versus a massive, but shallow, concrete, and steel spread footing. The micropile system resists both compression (weight) and uplift (wind overturning) forces. The micropile system also is being considered for offshore wind turbines (Offshore Engineer 2021). The corrosion resistant PVC-glass micropiles would be compatible with the seawater environment. The PVC-glass composite has 2 times the strength to weight ratio versus steel and, unlike concrete, it has a high tensile strength that is used to counteract uplift (overturning) forces. Therefore, the total foundation weight (tons of material) should be reduced by over 80% for the PVC-glass composite micropile design versus the typical concrete and steel spread footing. The green PVC material also sequesters a ton of CO_2 per ton of PVC.

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