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Quantifying the fuel consumption, greenhouse gas emissions and air pollution of a potential commercial manganese nodule mining operation

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Abstract:

Manganese nodules contain economically valuable metals which may be mined in the future to supply metals to a growing world population. Thus far, environmental research has focused mainly on impacts occurring at the seafloor or in the water column but largely neglected any impacts caused above the sea surface. Emissions of greenhouse gases and other air pollutants contribute to, inter alia, global warming, acidification and photo- chemical ozone formation, which all negatively affect ecosystems and humans. We quantify the annual fuel consumption and emissions associated with a potential nodule mining operation in the Clarion-Clipperton Zone with an annual production of 3 million dry tons. We base the assessment on publicly accessible energy demand estimates from three different studies and complement this with a calculation of the fuel demand and emissions of nodule transport scenarios to three different destinations. The global warming, acidification and photo- chemical ozone formation potentials range between 82,600–482,000t CO_2-equivalent (-eq.), 1,880–11,197t SO_2-eq., and 1,390–8,734 t NO_x-eq., respectively, depending on factors including the engine loads, specific fuel oil consumption and transport speeds. We then discuss the regulatory dimension surrounding the topic. As three separate regimes (climate change, deep-sea mining and shipping) are applicable, we analyze the applicable framework and provide an outlook for the future regulation of DSM-related GHG emissions.

1. Introduction

Marine mineral deposits like manganese nodules (nodules), cobalt-rich ferromanganese crusts (crusts) and seafloor massive sulfides (SMS) contain substantial amounts of metals, which serve as important raw materials for a variety of applications ranging from construction material to electronic devices and renewable energy technology (1–5). Deep-sea mining can take place in coastal states' territorial seas or exclusive economic zones (EEZs), or in international waters ('the Area'), where no sovereignty can be asserted. As is the case with terrestrial mining, deep-sea mining will cause environmental impacts, which have already been thoroughly examined by various national and international multidisciplinary initiatives, such as the Deep Ocean Mining Environment Study (DOMES, 1972-1981 (6), the Disturbance and Re-Colonisation Experiment (DISCOL, 1989) (7), the Japan Deep-Sea Benthic Experiment (JET, 1994) (8), the EU-project "Managing Impacts) of Deep-Sea Resource Exploitation" (MIDAS, 2013-2016) (9) and the Joint Programming Initiative – Ocean's projects "Ecological Aspects of Deep-Sea Mining" and "MiningImpact" (2015-2022) (10). Until now, the environmental research focused mainly on impacts occurring at the seafloor, such as habitat destruction due to the removal of hard substrate and the suspension and re-deposition of sediment, as well as the creation of potentially far-reaching particle plumes in the water column (11–14). Impacts expected to occur above the sea surface, such as greenhouse gas emissions and air pollution have been mostly neglected.

As widely agreed, upon, nodule mining operations will consist of mining vessels from which the mining equipment will be deployed, as well as a number of bulk carriers or shuttle barges, which will transport the mined materials to shore for further processing on land. The nodules, which formed through the precipitation of metals from seawater and sediment pore water over the course of millions of years, are located in water depths between 3,500 and 6,000 m (4). They will be harvested by one or more collector vehicles and then lifted to the surface via a riser pipe. Onboard the mining vessel the nodules will be washed, partially dried and stored until they can be transshipped onto a transport vessel. The remaining sediment and seawater from the cleaning process will be discharged into the water column, preferably at near-seafloor depth (15–19).

On the high seas, hundreds of nautical miles away from the coasts, heavy fuel oil (HFO) is the most commonly used marine fuel in international shipping (16,20).The combustion of HFO, however, causes the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as other pollutants like nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs) and particulate matter (PM), which contribute to global warming, acidification and photochemical ozone formation. Anthropogenic greenhouse gas emissions and air pollution are global problems and their cumulative impacts threaten ecosystems and human health (21,22).

To contribute to the holistic assessment of potential environmental impacts of deep-sea mining, we present a methodology to systematically quantify the fuel consumption and emissions that could be associated with a potential typical nodule mining operation in the Clarion-Clipperton Zone (CCZ). Fuel demand forms a significant component of the flexible costs of mining operations and consequently affects the feasibility of such undertakings. Moreover, current and future emission regulations could affect deep-sea mining and the transportation of minerals from the mine site to shore and should, therefore, be considered early in the planning process. Lastly, the quantification of fuel and electricity consumption and the corresponding release of emissions can serve as a starting point for the comparison between deep-sea mining and equivalent terrestrial mining processes.

As deep-sea mining operations have not yet started, there is currently no reliable information available in the energy consumption of commercial-scale nodule mining projects. Moreover, technology developers usually handle energy consumption data from experimental tests confidentially. Therefore, it is only possible at this point to use publicly accessible energy demand estimates published as part of economic feasibility studies or life-cycle assessments. We, therefore, base our analysis on two economic assessments published by Ramboll & HWWI (17) and Agarwal et al. (15), as well as a life-cycle assessment by McLellan (16). We complement the quantification of the fuel consumption and emissions of the mining operation with our own calculation of the fuel demand associated with the transportation of the nodules to three possible destinations. Following this, we evaluate the results with respect to the three environmental impact categories 'global warming potential', 'acidification potential' and 'photochemical ozone formation'. Lastly, we discuss the issue of greenhouse gas emissions and air pollution in relation to deep-sea mining in a wider policy context and highlight knowledge gaps that should be addressed prior to the commercialization of the activity. We refrain from including the transportation and metallurgical processing of the nodules on land for reasons related to the limited data availability and accessibility at the current state of development (23).

2. Emissions from combustion of HFO in ship engines

The combustion of HFO causes emissions of various greenhouse gases and air pollutants. The quantity of emissions released during the operation of an engine can be influenced by various factors including fuel type, engine type, or installed abatement technology (21). During combustion, the carbon stored within the fuel is almost completely emitted as CO_2. The CO_2 emissions are, thus, directly linked to the sulfur (S) content of the fuel, which in HFO typically lied between 2 and 3 % but can also reach up to 5%. The incomplete combustion of hydrocarbons causes the release of CH_4, CO, NMVOCs and PM. CO emissions indirectly influence the atmospheric concentration of CH_4 in the atmosphere by reacting with hydroxyl radicals, which would otherwise serve as a sink for CH_4. NMVOC emissions are influenced by fuel type and engine type. NO_x emissions usually comprise nitric oxide (NO) and nitrogen dioxide (NO_2) and are influenced by fuel type and engine type (21,24).

The release of greenhouse gases and other air pollutants are a function of activity and calculated as the product of the fuel consumption and a pollutant, fuel-type, and engine type specific emission factor (EF) (21,24,25). EFs are representative values that link a certain activity to the amount of emissions this particular activity causes per reference unit. They do not, however, provide information on the impact of the respective pollutant. For instance, the EFs can be used to quantify the CO_2, CH_4, and N_2O emissions caused by combusting a certain amount of HFO but they cannot account for the fact that CH_4 and N_2O are considerably more potent greenhouse gases than CO_2. This needs to be considered in a second calculation step using so-called characterization factors (see section?).

Table 1 shows the EFs recommended for slow-speed (main) engines and medium-speed (auxiliary) engines compiled by the International Maritime Organization (IMO) as part of their Third Greenhouse Gas Study (24). The values used in the IMO's study were either directly published in official IMO documents, for example in resolutions of the IMO's Marine Environmental Protection Committee (MEPC), or reviewed, discussed, and unanimously agreed upon by the consortium members authoring the IMO's study (for more information see (24), Annex 6, p. 247).

3. Methodology

There are different methods available for the calculation of emissions from the international shipping fleet (top-down and bottom-up), which are selected based on the purpose of the assessment (i.e. the required resolution), the availability of data and the pollutant under consideration (21,25). The Tier 1 method is a top-down approach and usually utilized in cases where a high resolution is not required, or data availability is limited. It is usually based on fuel sales statistics and only differentiates between fuel types. The Tier 2 approach is more specific as it additionally distinguishes engine types and uses country specific EFs wherever possible (21,25). The Tier 3 approach is a bottom-up method that estimates emissions based on individual ship data. It considers not only fuel and engine types but also operational modes such as cruising, maneuvering, at anchorage (sailing at 1-3 knots) or at berth (sailing at <1 knot) (24).

For the calculation of greenhouse gas emissions and air pollution resulting from deep-sea mining, we combine Tier 1 and Tier 3 approaches, as the focus is on specific vessels only. For the quantification of CO_2, N_2O, NO_x, and SO_x we follow the Tier 1 approach as these emissions are solely influenced by fuel type. For the calculation of CH_4, CO, PM, and NMVOC emissions we use the Tier 3 approach to differentiate between engine type and operational modes (only for the transport vessels, as the mining vessel remains mostly stationary). Concerning engine types, we assume that the energy required for the propulsion of the mining and transport vessels is generated by the ship's main engine (slow-speed diesel engine), whereas electricity for the operation of the mining equipment is generated by its auxiliary engine(s) (medium-speed diesel engine(s)). For the quantification of the fuel consumption of the mining and transport vessels we follow the steps outlined in this section using the parameters presented in Tables 2 and 3. The set-up and scope of a hypothetical commercial nodule mining operation is described in section 4. For the purpose of this assessment, we did not account for the speed of the mining vessel in addition to the energy demand allocated to propulsion. For comparison, a bulk carrier vessel (58,000 DWT) moving at the speed of the mining collector (0.5 m/s or 0.97 knots) would consume about 0.13 t/d.

1) The fuel consumption of the mining equipment and vessel is calculated as follows:

$$C_{mining,annual} = \left[\left(EC_{\mathrm{ME,\ annual}} \times SFOC_{\mathrm{ME}}\right) + \left(EC_{\mathrm{AE,\ annual}} \times SFOC_{\mathrm{AE}}\right)\right]$$

where

- $C_{mining,\ annual}$ = Annual fuel consumption of mining equipment and vessel [t]
- $SFOC_{ME}$ = Specific fuel oil consumption main engine [t/kWh]
- $SFOC_{AE}$ = Specific fuel oil consumption auxiliary engine [t/kWh]
- $EC_{ME,\ annual}$= Annual energy demand of the mining vessel's main engine [kWh]
- $EC_{AE,\ annual}$ = Annual energy demand of the mining vessel's auxiliary engine [kWh]

2) The GHG emissions of the mining vessel and equipment is calculated as follows:

$$E_{p,mining} = C_{mining,annual} \times EF_p$$

where:

- $E_{p,\ mining}$ = Emissions of pollutant p from mining equipment and vessel
- $C_{mining,\ annual}$ = Annual fuel consumption of mining equipment and vessel [t]
- EF_p = Emission factor for pollutant p

In cases where the EF differs for main and auxiliary engines, the emissions have to be calculated separately with the appropriate EFs and summed afterwards.

The transport component

The fuel consumption needed for the transport of the mineral ores requires the determination of several parameters such as engine power and engine load factor, ballast load factor, travel distance, speed and the specific fuel consumption (SFOC) of the main and auxiliary engines. Furthermore, it is important to determine the time spent in cruising mode, at anchorage, and at berth, as this affects the operation of the engines. Lastly, it is necessary to determine how many transport cycles are needed per year based on the annual production of the mine and the storage and transport capacity of the mining and transport vessels. Each transport cycle consists of a single distance traveled in laden condition, one in ballast condition, as well as time for transshipment at sea and in port at either end of the trip. While the main engine is operated only during sailing, the auxiliary engines are running permanently, i.e. during sea passage and (un)loading operations.

1) Calculation of the required main engine power at desired speed:

$$M_{ME,d} = l_{ME} \times M_{ME} \times (d/D)^2$$

Where:

- *$M_{ME,d}$ = Main engine output at desired speed [kW]*
- *M_{ME} = Maximum load of main engine [kW]*
- *l_{ME} = load factor of main engine, in this case 0.85*
- *D = design speed (maximum speed according to vessel manufacturer) [NM/h]*
- *d = desired speed [NM/h]*

2) Calculation of daily fuel consumption of the main engine at desired speed:

$$C_{ME,\ daily,\ d} = M_{ME,d} \times SFOC_{ME} \times 24$$

Where:

- *$C_{ME,daily,d}$ = daily fuel consumption at desired speed d [t]*
- $M_{ME,d}$= *Main engine load at desired speed [kW]*
- *d = design speed [NM/h]*
- *$SFOC_{ME}$ = Specific fuel oil consumption [g/kWh]*

3) Calculation of the annual fuel consumption of the main engine for N round trips (round trips consist of a single voyage in laden condition and one voyage in ballast condition, as well as time at anchorage and at berth).

$$C_{ME,annual} = \left[\left(C_{ME,\ daily,\ d} \times t_d\right) + \left(b \times C_{ME,\ daily,\ d} \times t_d\right)\right] \times N$$

Where:

- $C_{ME,annual}$ = *total annual fuel consumption of the transport vessels‘ main engines at desired speed d [t]*
- t_d = *travel time for one-way transport between mining operation and port [d]*
- *b = ballast load factor, in this case 0.85 (reduction factor for operation in ballast condition, i.e. reduced resistance due to smaller ships displacement)*
- *N = number of round trips per year*

4) Calculation of the total fuel consumption of the transport vessels’ auxiliary engines:

The calculation of the annual fuel consumption of the auxiliary engines largely follows that of the main engine. It is affected by the time spent in each operational mode. For the auxiliary engine, it is not important to differentiate whether the ship travels in laden or ballast condition.

$$C_{AE,annual} = \Big((M_{AE,s} \times SFOC_{AE} \times t_s) + (M_{AE,b} \times SFOC_{AE} \times t_b) + (M_{AE,a} \times SFOC_{AE} \times t_a)\Big) \times N$$

Where:

- $C_{AE,annual}$ = *total annual fuel consumption of auxiliary engines [t]*
- $M_{AE,\,s}$ *Engine load of the auxiliary engine (cruising) [kW]*
- $M_{AE,\,a}$ *Engine load of the auxiliary engine (at berth) [kW]*
- $M_{AE,\,b}$ *Engine load of the auxiliary engine (at anchorage) [kW]*
- t_s = *time spent cruising [h]*
- t_b = *time spent at berth [h]*
- t_a= *time spent at anchorage [h]*
- *N = Number of round trips per year*

5) Calculation of the total fuel consumption from transportation of mineral ores:

$$C_{total,annual} = C_{ME,annual} + C_{AE,annual}$$

Where:

- $C_{ME,annual}$ = *total annual fuel consumption of main engines [t]*
- $C_{AE,annual}$ = *total annual fuel consumption of auxiliary engines [t]*
- $C_{total,annual}$ = *total annual fuel consumption of main and auxiliary engines [t]*

6) Calculation of emissions from transportation of mineral ores:

$$E_{p,transport} = C_{transport,\ annual} \times EF_p$$

Where:

- $E_{p,transport}$= Emissions of pollutant p from mining equipment and vessel
- $C_{transport, annual}$ = Annual fuel consumption of mining equipment and vessel [t]
- EF_p = Emission factor for pollutant p

Table 1: Table 2: Emission factors for main (EF ME) and auxiliary (EF aux) engines recommended in the Third IMO Greenhouse Gas Study (24)

Type of emission	**EF ME [t CO2/t HFO]**	**EF AUX**	**Reference**
CO_2 (default)	3.114	3.114	MEPC 63/23, Annex 8
CO_2 (incl. upstream emissions from HFO production and transport)	3.5	3.5	(26,27)
CH_4	0.00006	0.00004	(28)
N_2O	0.00016	0.00016	(29)
CO	0.0026	0.0024	(30)
NO_x	0.079	0.049	(24)
SO_x (HFO sulfur content 2.7%)	0.053	0.053	(24)
PM	0.00728	0.00634	(29)
NMVOC	0.00308	0.00176	(31)

4. Case study: nodule mining in the CCZ

In the absence of publicly accessible data on existing commercial- scale technology, we base our assessment on energy demand estimates presented in the literature by Agarwal et al. (15), McLellan (16), and Ramboll & HWWI (17) (Figure 1). While the three mining systems are generally similar, they differ with respect to the number of collector vehicles or mining vessels in operation, as well as the annual production and operational time. For instance, Agarwal et al. (15) propose a modular mining system capable of mining 1.5 million dry tons per year, consisting of 9 hybrid-type collector vehicles, which are attached to three mining vessels (3 collectors per vessel). The collector vehicles are modeled based on the South Korean MineRo experimental collector (32) although a hydraulic type is chosen instead of the original hybrid type. The collector vehicles are connected via flexible riser pipes to a joint black box, which acts as a buffer to ensure an even flow of nodule material. From the buffer the nodules are pumped upward to the mining vessel through a shared rigid riser pipe. Onboard the mining vessel, which is equipped with a dynamic positioning system, the no- dules are washed, dewatered, partially dried and stored until pick up by ore shuttle barges occurs. One mining system consisting of a mining vessel and three collector vehicles requires 16.2 MW (11.5 MW equipment, 4.7 MW mining vessel), amounting to approximately 50 MW for the entire mining operation (1.5 million dry tons of nodules retrieved from 5,000 m water depth). McLellan (16) uses a similar mining concept, which, however, relies on only one mining vessel and one collector vehicle to produce 1.5 million tons of dry nodules per year. The energy consumption of the mining equipment is a direct proportional scale-up of the Indian Integrated Mining System described by Atmanand (31). The hydraulic system was tested in the Central Indian Ocean using artificially produced and distributed nodules at a water depth of 500 m. The energy consumption to mine 1.5 million dry tons of nodules at a water depth of 5,000 m amounts to about 30 MW (23 MW equipment, 7 MW mining vessel). The mine set-up envisioned by Ramboll & HWWI (17) builds on recent findings of the European Union's Blue Mining and Blue Nodules projects and centers around a hydraulic mining system consisting of two collector vehicles, which are connected to a buffer by means of flexible riser pipes. From the buffer, which ensures a continuous and even flow, the nodule material from both collector vehicles is pumped upward to the mining vessel through a rigid riser pipe. Onboard the mining vessel, which is equipped with active propulsion and dynamic positioning, as well as onboard handling and transport systems and storage facilities, the nodules are washed and stored until they are picked up by two to three bulk carrier vessels and transported to shore. The energy demand for a nodule operation with an annual production of 3 million dry tons of nodules is estimated to be 16.37 MW (14.12 MW equipment, 2.25 MW mining vessel) based on the company's long-time experience in the offshore engineering sector. To make all of the energy demand estimates comparable, we adjusted them to fit a nodule mining operation at 5000 m water depth, which is operational over 300 days per year with an annual production of 3 million dry tons (34)

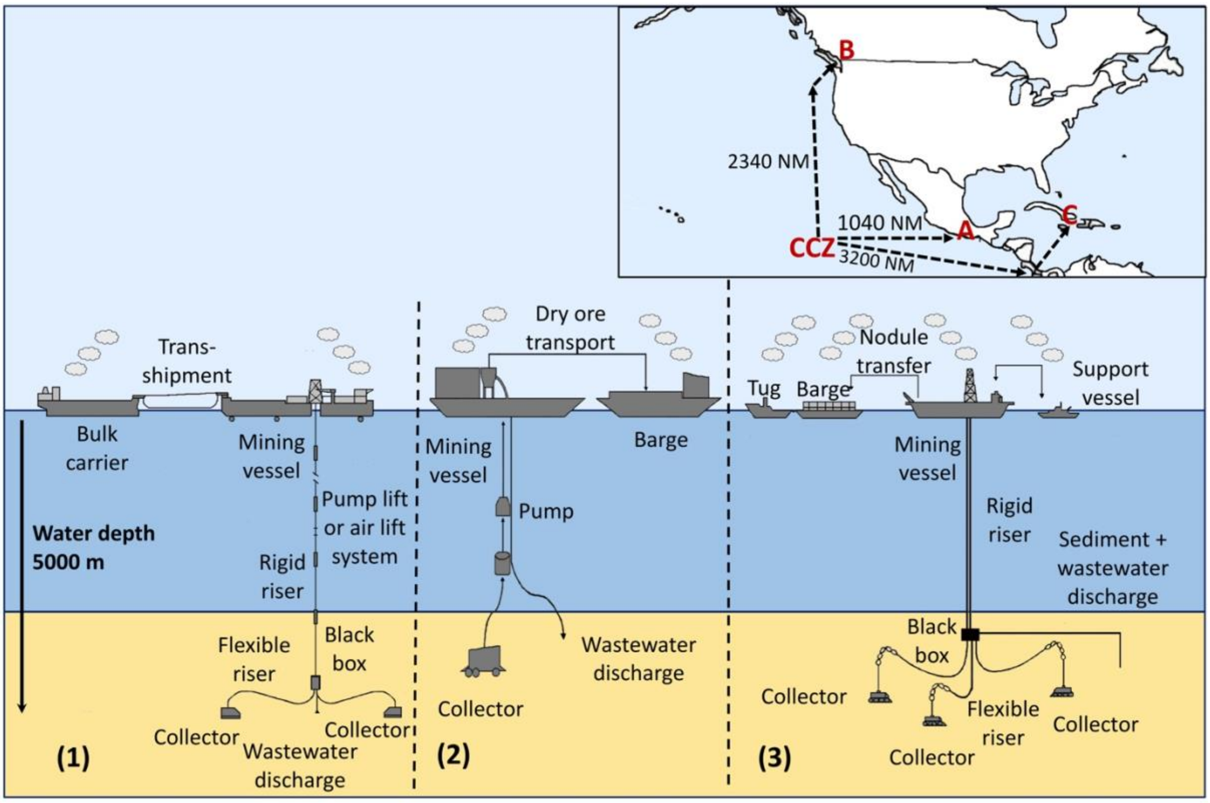

Figure 1: Schematic overview of the mining concepts outlined by and modified after (1)

Ramboll & HHWI (17)*, (2) McLellan* (16) *and (3) Agarwal et al.*(15) *as well as a schematic overview of the transport locations (A) Port of Lazaro Cardenas, Mexico, (B) Port of Vancouver, Canada, and (C) Port of Santiago de Cuba, Cuba*

We calculated the fuel consumption and the corresponding emissions for three transport routes to three different possible processing locations on land (Fig. 1). The first destination port is Lázaro Cárdenas in Mexico (1,040 NM), which is the port located closest to the CCZ. Due to its relative proximity to the CCZ, this option is the most economical option. The second potential transport destination is the Port of Vancouver in Canada (2,340 NM), which is a suitable processing location from a sustainability-focused point of view due to the larger share of renewable energy in the Canadian energy mix (35,36). The third transport destination is the Port of Santiago de Cuba in Cuba (3200 NM). Cuba may be a suitable processing location due to its relative proximity to the CCZ and the country's experience with the processing of terrestrial nickel laterites, which are considered to be similar to nodules in this regard (23). For the purpose of this study, we assume that bulk carriers carry out the transport of fuel, personnel, and no- dules. Tables 2 and 3 show the assumptions of the input values for the calculation of the fuel consumption associated with the mining and transport vessel and the mining equipment

Table 3: Energy demand estimates for a hypothetical mining operation with an annual production of three million t of nodules (dry weight) based on assessments by Ramboll & HWWI (17)*, McLellan* (16) *and Agarwal et al.* (15)

Energy demand estimates (per 3 million t/yr dry weight)		
Ramboll & HWWI (17) Mining vessel: 2.25 MW Mining equipment: 14.1 MW	*McLellan* (16) Mining vessel: 14 MW Mining equipment: 46 MW	*Agarwal et al.* (15) Mining vessel: 78 MW Mining equipment: 191.7 MW
Annual production: 3 million t (dry weight)		
Annual operational time: 300 d		
Water depths: 5,000 m		
Specific fuel oil consumption (SFOC) main engine: 170 g/kWh (based on the General Arrangement Plan of a bulk carrier vessel of similar size), 195 g/kWh(24) ((24), used as default value, if not indicated otherwise)		
Specific fuel oil consumption (SFOC) auxiliary engine: 227 g/kWh		

Table 4: Overview of input values for the transport vessels

Engine load
Main engine
Maximum engine load (100%): 8400 kW (based on the General Arrangement Plan of a bulk carrier vessel of similar size)
Engine Load factor: 0.85 (based on the General Arrangement Plan of a bulk carrier vessel of similar size)
Engine load at design speed (14.5 knots): 7410 kW (based on the General Arrangement Plan of a bulk carrier vessel of similar size)
Engine load at desired speed (12 knots): 4890.2 kW
Ballast load factor: 0.85
Auxiliary engine
Engine load: at sea 260 kW, at berth 370 g/kWh, at anchorage 260 kW (average values provided by (24)
Specific fuel oil consumption
Main engine
Specific fuel oil consumption (SFOC): 170 g/kWh (based on the General Arrangement Plan of a bulk carrier vessel of similar size), 195 g/kWh (24) used as default value, if not indicated otherwise)
Auxiliary engine
227 g/kWh (24)

Time considerations
Main engine
Time required for single distance at 12 knots: 3.61 d (Mexico), 8.15 d (Canada), 11.11 d (Cuba)
Time required for single distance at 14.5 knots: 2.99 d (Mexico), 6.74 d (Canada), 9.19 d (Cuba)
Aux engine
Time required for single distance at 12 knots: 3.61 d (Mexico), 8.15 d (Canada), 11.11 d (Cuba)
Time required for single distance at 14.5 knots: 2.99 d (Mexico), 6.74 d (Canada), 9.19 d (Cuba)
Time of loading/unloading (transshipment): at berth 2 days, at anchorage 1.5 days (loading rate: 2000 t/h + buffer)
Number of round trips per year: 60 (assuming an annual production of three million dry tons and a bulk carrier transport capacity of 50,000 t of dry nodules.

5. Results

5.1. Quantification of HFO consumption and associated emissions to air

Figs. 2–10 depict the results of the calculation of the annual fuel consumption and resulting emissions of the hypothetical mining operation in the CCZ and the three transport scenarios (Figs. 2 and 3), as well as the corresponding emissions of CO_2 (Figs. 3–10), CH_4 and N_2O emissions (Figs. 7 and 8) and CO, PM, NMVOCs, NO_X, and SO_X (Figs. 9 and 10). All results refer to an annual production of three million dry tons of nodules, mined at 5,000 m water depth over an annual operational time of 300 days. For every transport scenario, we varied the specific fuel oil consumption of the main engine ($SFOC_{ME}$) between 175 and 195 g/kWh and the transport speed between 12 and 14.5 knots to understand the implication of these variations. While the majority of the figures show the emissions of various pollutants for the mining operation (mining vessel and equipment) only, Fig. 4 compares the contributions of the mining vessel, the mining equipment and the transportation of the nodules. Fig. 5 compares the three different transportation scenarios, also varying the $SFOC_{ME}$ and the transportation speed. Fig. 6 considers the well-to-wheel emissions of the mining operation (mining vessel and equipment), which incorporate not only the emissions caused by the combustion of the HFO on site but also the emissions caused during the production of the HFO and its transport to the vessels. The fuel consumption is multiplied with an EF specifically for the calculation of well-to-wheel emissions of bulk carrier vessels. The demand estimates for the mining operation (mining vessel and equipment) translate to approximately 26,100t HFO, 95,000t HFO, and 423,240 t HFO for the Ramboll & HWWI (17), the McLellan (16), and the (15) set-ups, respectively. The transportation of no- dules to Mexico, Canada and Cuba by means of Supramax bulk carrier vessels requires 10,157t HFO, 22,447t HFO, and 30,465t HFO, respectively. Common to all three mining scenarios is the assumption that energy consumption of the mining equipment is higher than that of the mining vessel and of the transport component. The latter, however, depends on the distance between the mine site and the port.

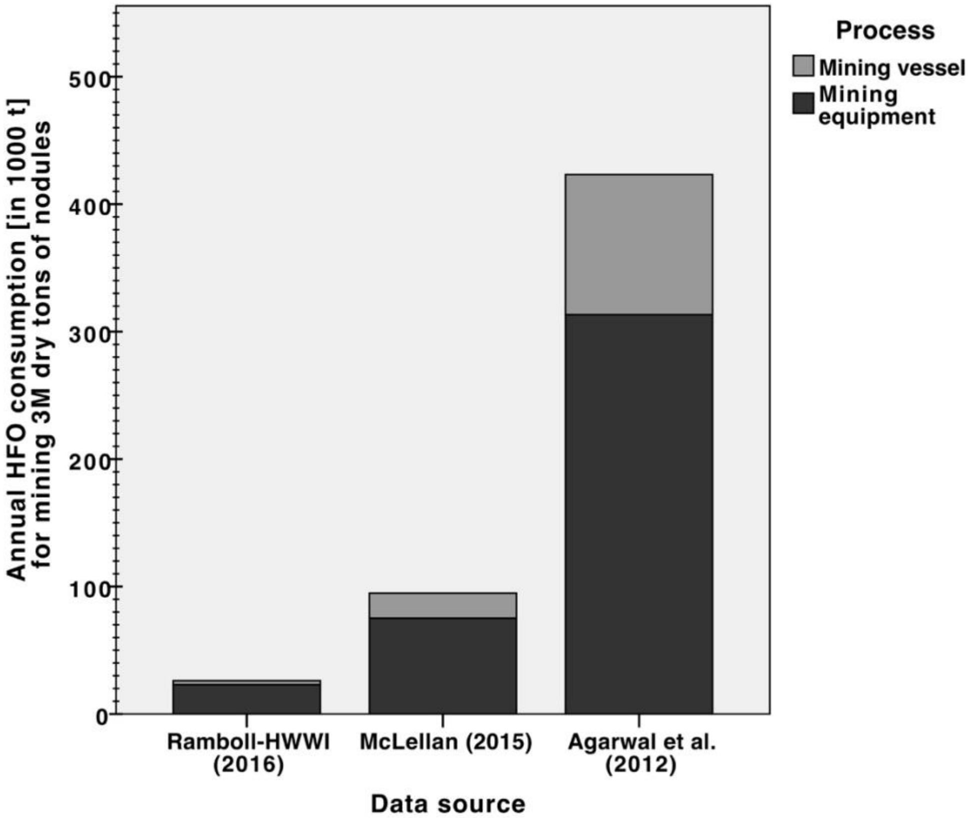

Figure 2: Annual HFO consumption of a 3 million dry t Mn nodule mining operation subdivided into mining vessel and mining equipment based on energy demand estimates from three different sources

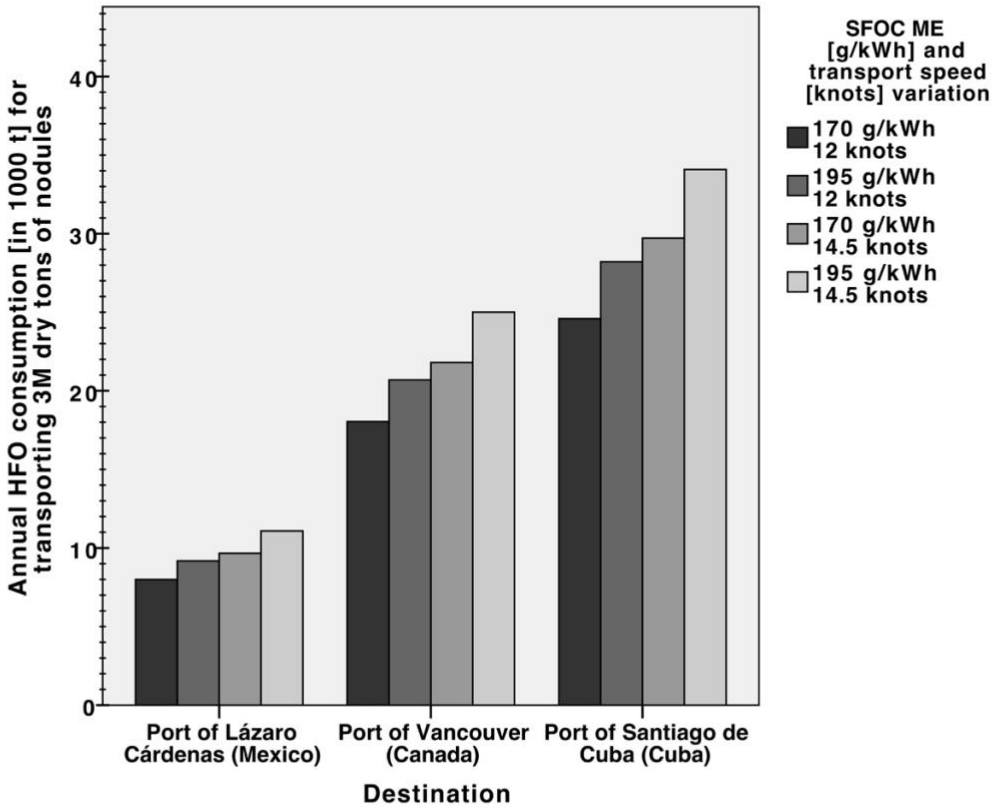

Figure 3: Annual HFO consumption for transport of 3 million dry tons of Mn nodules to different destinations.

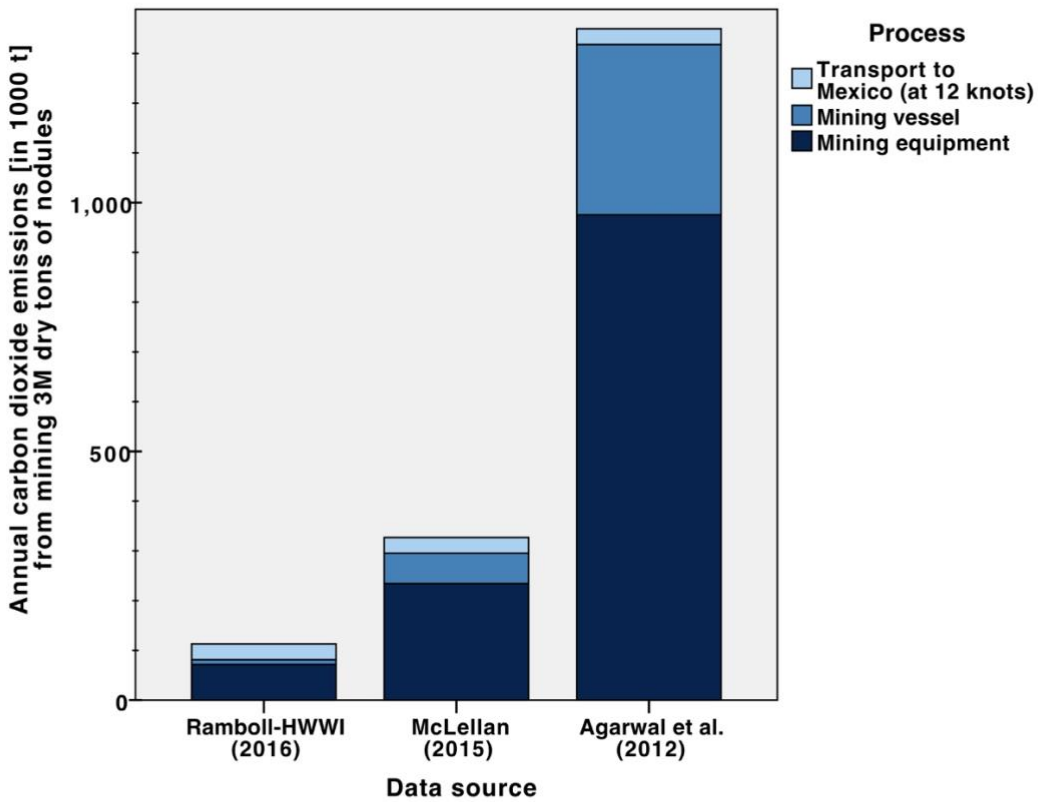

Figure 4: Annual CO_2 emissions a 3 million dry t Mn nodule mining operation subdivided into mining vessel, mining equipment and transportation (from the CCZ to Mexico) based on energy demand estimates from three different sources.

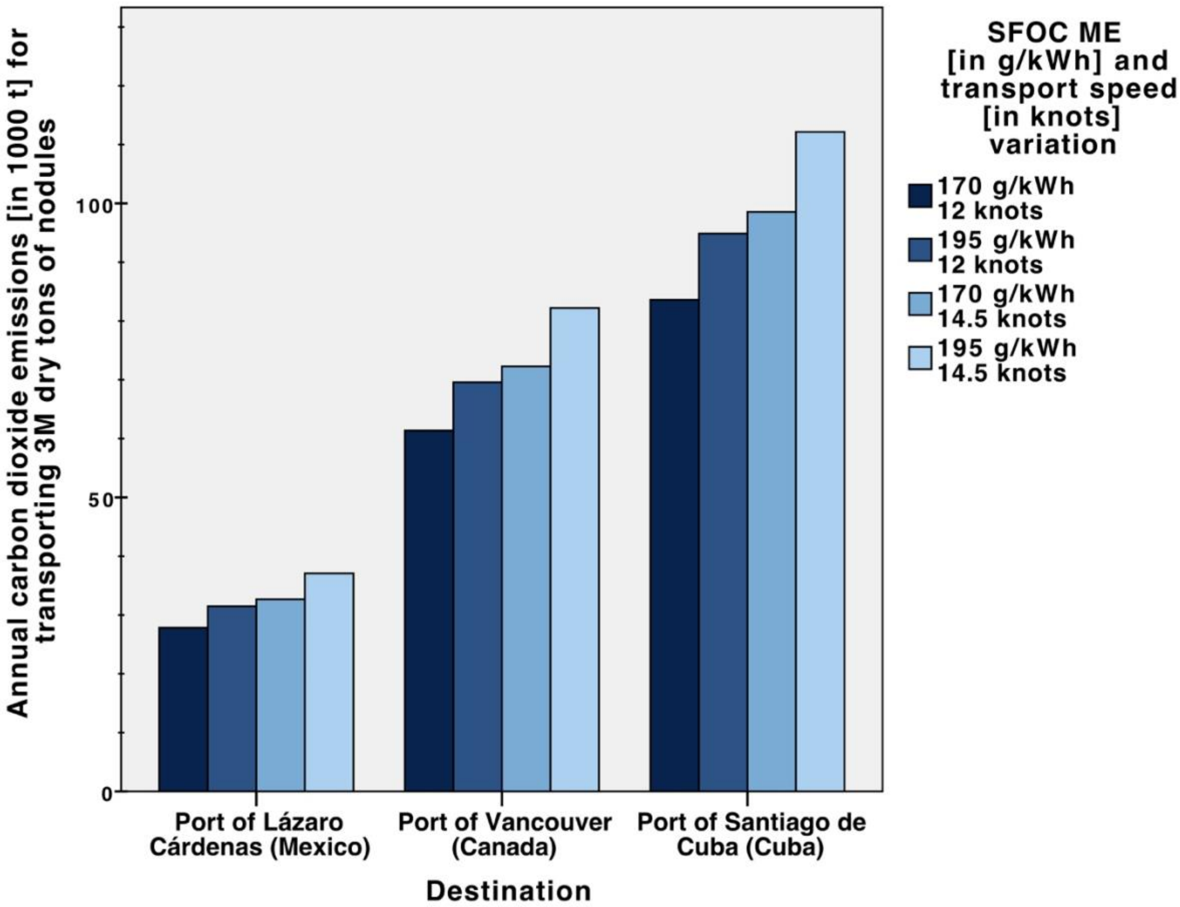

Figure 5: Annual CO_2 emissions for transport of 3 million dry tons of nodules from the CCZ to different locations with variations of the specific fuel oil consumption of the main engine (SFOC ME) and the transport speed.

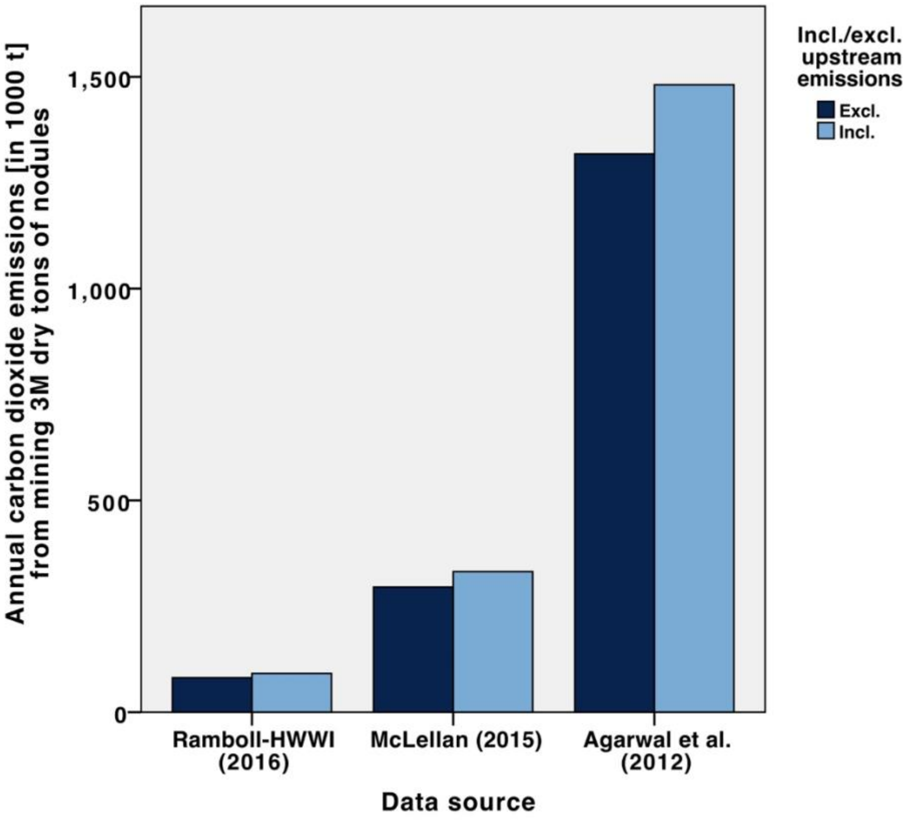

Figure 6: Annual CO_2 emissions for a 3 million dry tons Mn nodule mining operation arising from the combustion of the HFO (excl. upstream emissions) and well-to-wheel (incl. combustion and upstream emissions) based on energy demand estimates from different sources.

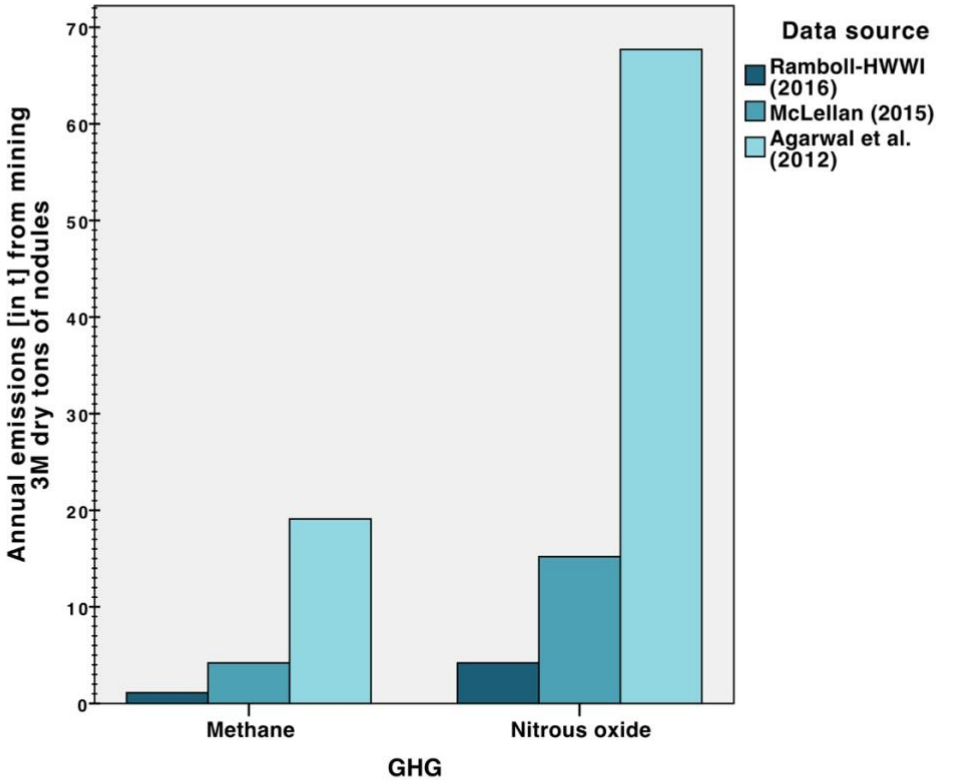

Figure 7: Annual CH_4 and N_2O emissions for a 3 million dry tons Mn nodule mining operation based on energy demand estimates from different sources.

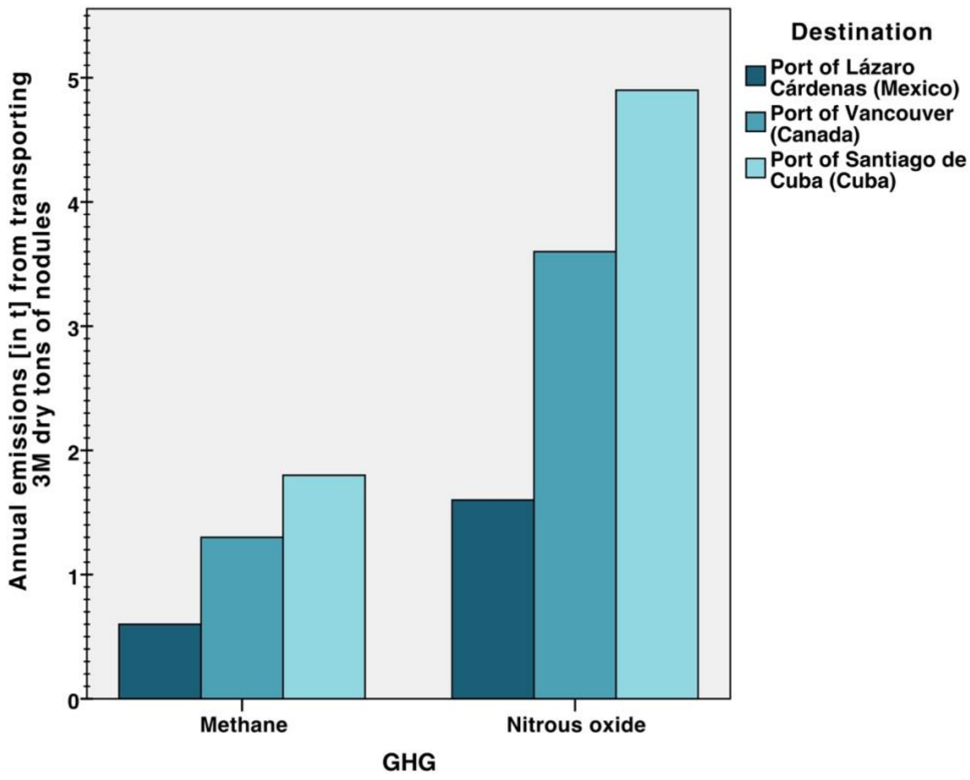

Figure 8: Annual CH_4 and N_2O emissions for transporting 3 million dry tons of Mn nodules from the CCZ to different destinations

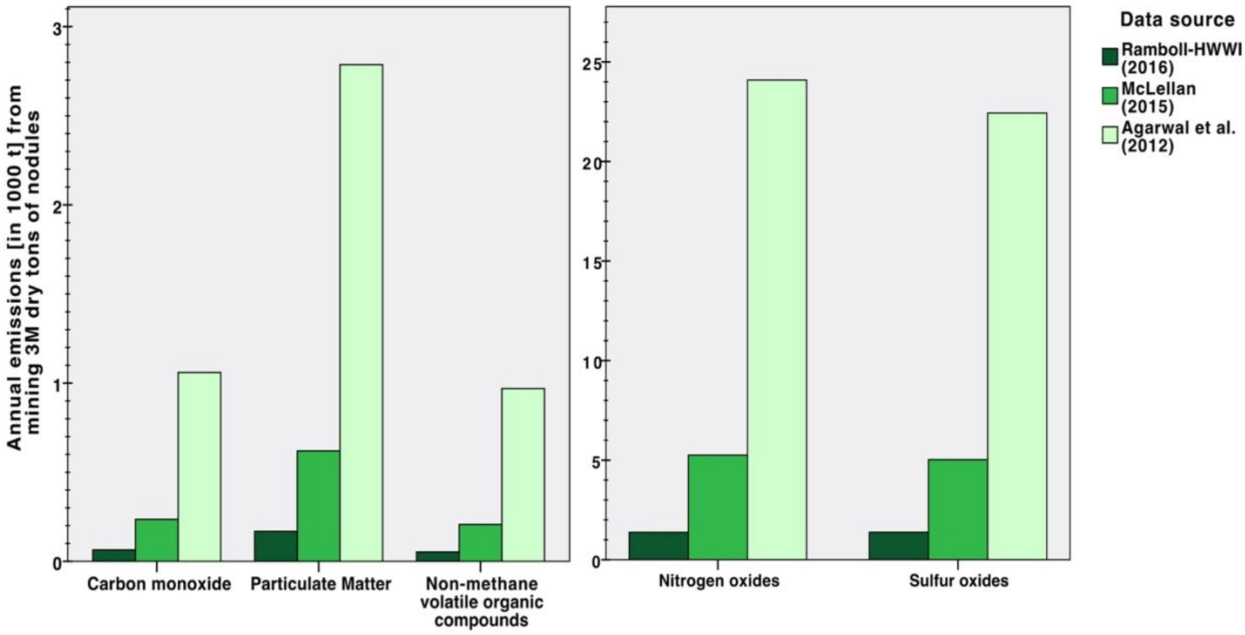

Figure 9: CO, PM, NMVOC, NO_x and SO_x emissions for a 3 million dry tons Mn nodule mining operation based on energy demand estimates from three different sources

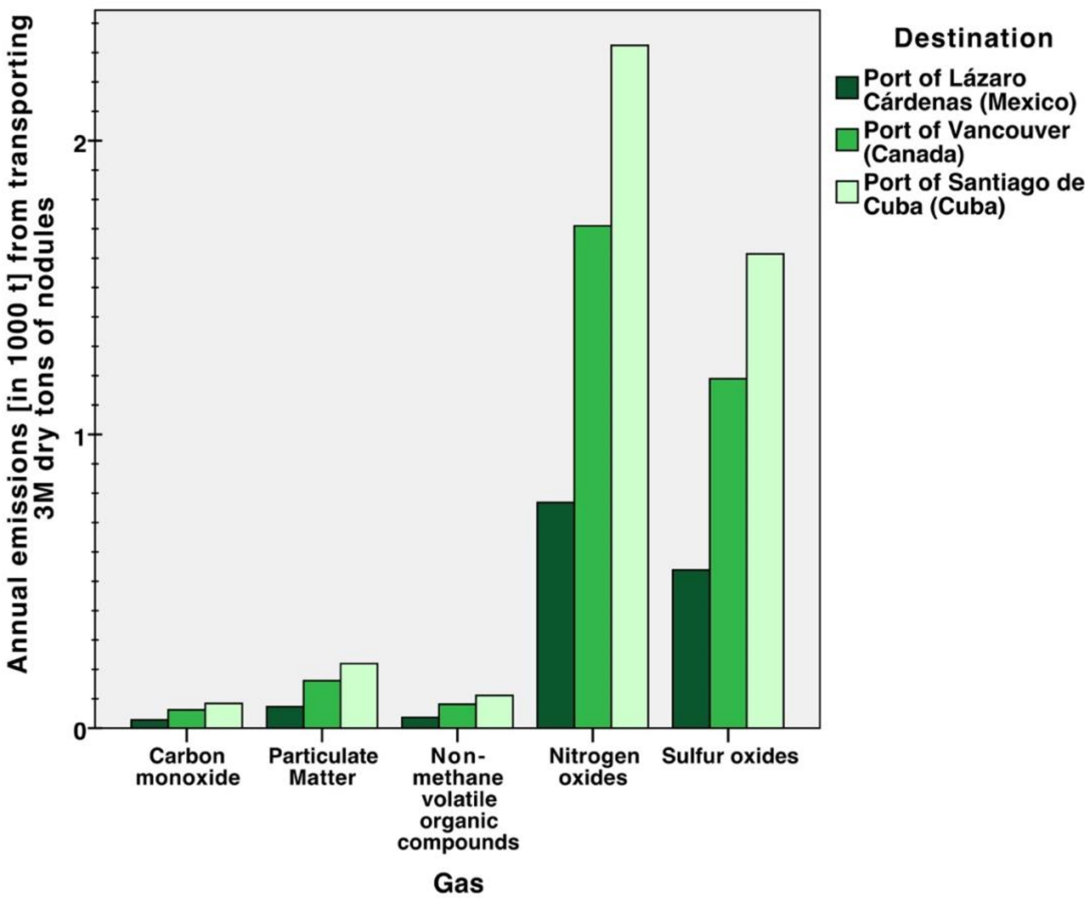

Figure 10: CO, PM, NMVOC, NO_x and SO_x emissions for transporting 3 million dry tons of nodules from the CCZ to different destinations

5.2. Impact assessment

Life-cycle impact assessment (LCIA) is a method to evaluate and compare different environmental impacts such as greenhouse gas emissions and air pollution with respect to their influence on ecosystem well-being and human health. The impacts are typically grouped into several impact categories suitable for the pollutants or processes under consideration (37). To make the pollutants contributing to the individual impact categories comparable, they are normalized through multiplication with pollutant specific characterization factors (CFs). In contrast to EFs (see section 2), CFs account for the magnitude of the impact of individual pollutants (22). LCIAs can evaluate environmental impacts occurring along a production chain at different stages of the impact pathway: at mid-point level (e.g., 'global warming', 'acidification potential', and 'photochemical ozone formation') or at end-point level (e.g., 'damage to human health', 'damage to ecosystems', and 'damage to resource availability'). For the purpose of this study, we decided to focus on mid-point level impacts. Assessments at mid-point level show lower uncertainty while those at end-point level provide more information about the relevance of individual impacts (22). Due to our focus on air pollution resulting from the combustion of HFO and the limited number of pollutants, we focus on the mid-point level categories 'global warming potential', 'terrestrial acidification,' and 'photochemical ozone formation.'

For the calculation of the 'global warming potential' we used CFs provided as part of the ReCiPe method (22). We set the resulting index, the ‚total global warming potential' (GWP) to the defined period of 100 years. Table 4 shows the GWP100, expressed in tons of CO_2 equivalent (t CO_2-eq.), for the hypothetical mining operation (mining vessel and equipment) outlined in section 4 based on the energy demand estimates provided by Ramboll & HHWI (15), McLellan (16), and Agarwal et al. (15) using default EFs. Emissions of SO_X and NO_X cause acidic deposition (e.g., 'acid rain'), which leads to soil acidification and is harmful to the majority of plant species. Table 5 shows, expressed as tons of NO_X equivalent (t NO_X-eq.), the total acidification potential in tons of SO_X equivalent (t SO_X-eq.) of the emissions caused by the mining operations (mining vessel and equipment). Furthermore, NO_X and NMVOC emissions contribute to photochemical ozone formation (table 6). Tropospheric ozone can cause respiratory stress, the inflammation of airways and lung damage. Besides human health, ozone can also negatively affect ecosystems, specifically plant growth, and seed production. It can also decrease their overall resilience to other stressors (38,39).

Gas	Emissions [in t]			Conversion factor ReCiPe (22)	GWP100 [in t CO_2-eq.]		
	Ramboll & HWWI (17)	McLellan (16)	Agarwal et al. (15)		Ramboll & HWWI (17)	McLellan (16)	Agarwal et al. (15)
CO_2	81294	295327	474469	1	81,294	295,327	474,469
CH_4	1	4	7	34	38	143	235
N_2O	4	15	24	298	1,252	4530	7271
Total GWP100 [t CO_2-eq.)					**82,584**	**300,000**	**481,975**

Table 5: Total acidification potential for mining 3M t (dry weight) of nodules ($SFOC_{ME}$: 195 g/kWh) (rounded values)

Gas	Emissions [t GHG]			Conversion factor ReCiPe (22)	Acidification potential [t SO2-eq.]		
	Ramboll & HWWI (17)	McLellan (16)	Agarwal et al. (15)		Ramboll & HWWI (17)	McLellan (16)	Agarwal et al. (15)
SO_2	1384	5026	8075	1	1384	5026	8075
NO_x	1380	5252	8671	0.36	497	1891	3122
Acidification potential [in t SO_2-eq.]					**1,881**	**6,917**	**11,197**

Table 6: Total photochemical ozone formation potential for mining 3M t (dry weight) of nodules ($SFOC_{ME}$: 195 g/kWh) (rounded values)

Gas	Emissions [t GHG]			Conversion factor ReCiPe (22)	Photochemical Ozone Formation [t NO_x-eq.]		
	Ramboll & HWWI (17)	McLellan (16)	Agarwal et al. (15)		Ramboll & HWWI (17)	McLellan (16)	Agarwal et al. (15)
NO_x	1380	5252	8671	1	1380	5252	8671
NM VOC	52	207	349	0.18	9	37	63
Photochemical ozone formation [in t NO_x-eq.]					**1,389**	**5,289**	**8,734**

6. Discussion of results

The results deliver a first indication of the potential level of emissions expected to arise annually as a direct consequence of nodule mining. However, it is important to note in this regard that the values are based on three sets of energy demand estimates derived from off-shore engineering experience and scale-ups of experimental tests rather than actual data from commercial-scale operations.

The energy demand estimates provided by Ramboll & HHWI (17), McLellan (16), and Agarwal et al. (15) are vastly different. Based on these estimates, the mining concept envisioned by Ramboll & HWWI (17), which assumes by far the lowest energy demand would be the most suitable to reduce greenhouse gas and air pollution. Recent estimates in unpublished reports appears to confirm an energy demand of this magnitude for a nodule mining operation with annual production of three million dry tons[1]. While the Ramboll & HWWI (17) energy demand estimates are based on the company's long-term experience in the field of offshore engineering, McLellan (16) bases his energy demand estimates on a direct upscaling of the collector vehicle developed and described by (19,33). This experimentally tested mine system consisting of a collector vehicle, crusher and a positive dis- placement pump was tested at 500m water depth using artificially produced and distributed nodules. To test for sensitivity, McLellan (16) further compared the results from the scale-up with the energy demand of a single mining tool developed for the Solwara I project, which aims at mining SMS deposits in the EEZ of Papua New Guinea. McLellan (16) also clearly states that the nodules will be lifted by means of a hydraulic lifting system. However, the energy needed to cut sulfides and hard rock during the sulfide mining process may be considerably higher than the demand for nodule mining. In fact, the energy demand provided by McLellan (16) appears to be higher than more recent unpublished estimates suggest. Agarwal et al. (15) proposed collector vehicle is inspired by the South Korean MineRo experimental collector, although Agarwal et al. (15) envision a hydraulic collector instead of the original hybrid- type. They expect the energy demand of both collectors to be of the same order of magnitude. However, the mine set-up consisting of nine collector vehicles and three mining vessels to mine 1.5 million dry tons of nodules per year is very unusual compared to the majority of pro- posed mining concepts (16,17,40,41). The energy demand (95.5 MW) also appears to be extraordinarily high. For comparison, the most powerful commercially deployed wind turbines have a power rating of 8.8 MW (offshore), trend increasing. This mining concept would probably be associated with very high capital and operational costs, which may severely affect the economic feasibility of the mining operation. With respect to the mining vessel, the differences in energy can likely be

[1] Kuhn, T. Bundesanstalt für Geowissenschaften und Ressourcen. Personal communication.

attributed to the dimensions of the vessels and the number of vessels required per mining system. For example, while the Ramboll & HWWI (17) claim to require one mining vessel with a length of 270 m and a width of 40 m to produce three million dry tons of nodules per year, Agarwal et al. (15) envision the use of three mining vessels of 170 m length and 40 m width to mine 1.5 million dry tons per year.

Once DSM comes into a more advanced planning and development stage, it will be necessary to update and refine these assessments, for example with respect to the choice of engine main and auxiliary engines, their specific fuel oil consumption and engine output, the mining equipment's’ energy demand at a commercial scale, the transport vessels under consideration, their fuel demand, route and speed, and the time spent in different operational modes. Moreover, it will eventually be possible to determine the energy demand required for hoteling, which depends on the number of workers and crew onboard the mining and transport vessels. Ramboll & HWWI (17), for example, assume the mining vessel to carry 58 workers, which based on their energy demand estimate would cause, inter alia, an additional 6,107 t CO_2, 97 t NO_X and 104 t SO_X for a mining operation with an annual production of 3 million dry tons of nodules. The contribution from the hoteling of workers may even be higher, as Van Nijen et al. (42) assume that 70 people will work onboard the mining vessel. The newly built mining vessel for the Solwara I project (‘Nautilus New Era’) could even provide space for around 199 workers (43). Commercial-scale mining operations may also require the use of Remotely Operated Vehicles (ROVs) and Seafloor Working Units (SWUs), which based on the Ramboll & HWWI (17) estimate would cause additional annual emissions of, inter alia, 5,090 t CO_2, 81 t NO_X, and 87 t SO_X. Furthermore, for the purpose of this assessment, we did not account for the transport of fuel, crew and supplies to the mining vessel. In the open ocean, it is likely that the mining vessel has to receive fuel via ship-to-ship bunkering. Drill ships, would cause, inter alia, an additional 6,107 t CO_2, 97 t NO_X and 104 t SO_X for a mining operation with an annual production of 3 million dry tons of nodules. The contribution from the hoteling of workers may even be higher, as Van Nijen et al. (42) assume that 70 people will work onboard the mining vessel. The newly built mining vessel for the Solwara I project (‘Nautilus New Era’) could even provide space for around 199 workers (43). Commercial-scale mining operations may also require the use of Remotely Operated Vehicles (ROVs) and Seafloor Working Units (SWUs), which based on the Ramboll & HWWI (17) estimate would cause additional annual emissions of, inter alia, 5,090 t CO_2, 81 t NO_X, and 87 t SO_X. Furthermore, for the purpose of this assessment, we did not account for the transport of fuel, crew and supplies to the mining vessel. In the open ocean, it is likely that the mining vessel has to receive fuel via ship-to-ship bunkering. Drill ships, which may be comparable to deep-sea mining vessels, typically have a bunkering capacity between 5,000 and 10,000 t (44). Seagoing bunkering vessels are capable of bunkering between 1,000 and 10,100 m^3 of HFO or MDO, which translates to about 990 t to 9,900 t HFO, respectively (ISO 8217:2017). Thus, assuming that a commercial-scale mining vessel has a bunker capacity of 9,000 t, a bunkering vessel with a capacity of 9,000 t would have to approach about 3, 11, or 47 times annually to supply fuel to the mining operations outlined by Ramboll & HWWI (17), McLellan (16), and Agarwal et al. (15), respectively. Ship-to-ship bunkering is challenging and mostly carried out in sheltered areas outside ports to decrease port congestion. Moreover, many ship-to-ship bunkering systems require good weather conditions and calm waters. For the purpose of commercial deep-sea mining, it may, therefore, be necessary to develop strong seagoing ship-to-ship bunkering vessels that can operate under moderate to rough weather conditions without risking oil spills that could cause harm to the environment.

With respect to the transport destinations, Mexico and Canada may be the most realistic options, as the transport to Cuba would have to occur through the Panama Canal, which causes a considerable time delay and additional costs for passages. Moreover, Cuba, which imports a significant quantity of oil from the economically and politically unstable Venezuela and is vulnerable to blackouts caused by extreme weather events, may not be capable of providing a stable electricity supply for the processing of nodules. With respect to the other two potential processing locations, there may be a tradeoff between the share of renewable energy in the destination country's energy mix and the transport distance to the shore.

7. Regulations of greenhouse gas emissions and air pollution

Greenhouse gas (GHG) emissions and air pollution resulting from deep-sea mining potentially fall within the general remit of at least three different international regimes that have environmental man- dates, namely on climate, on deep-sea mining, and on shipping. While in principle these three regimes function independently from each other, they could intersect concerning governance in a specific area, e.g., targeting emissions resulting from vessels connected to potential mining operations. The following sections analyze the current state of and interplay between these three regimes with a view to regulating these types of emissions and aim at identifying different legal and practical measures that would require development if mining operations were to gain momentum.

7.1. The climate regime

Confronted with the scientific consensus that anthropogenic GHG emissions are the chief cause of global warming, which if left unabated would be dangerous to the well-being of ecosystems and humans, a concentrated international effort to address GHG emissions culminated in the conclusion of the United Nations Framework Convention on Climate Change

(UNFCCC) back in 1992 (45). The ensuing Kyoto Protocol set binding emission reduction targets on its parties through to commitment periods from 2008 to 2012 and 2013–2020 (46). As these commitments under the Kyoto Protocol will expire at the end of 2020, States will eventually be required to reduce their GHG emissions from their so-called nationally determined contributions (NDC) pursuant to pursuant to the recently concluded Paris Agreement (47). To date, it appears that the topic of DSM and its potential GHG emissions is yet to be discussed in the climate context. This should come as no surprise, as DSM projects in the CCZ focus on the international seabed and its resources, a global commons that is subject to rules of non-appropriation. As such, at least prima facie, the potential GHG emissions from DSM activities at mining sites could or should rather fall within the purview of the DSM regime. Likewise, given the fact that international shipping, just like aviation, is a transnational activity involving a wide range of actors subject to differing jurisdictions, it has been agreed within the climate regime that ship emissions should better be addressed under the shipping regime. While the climate regime does not occupy the field with respect to tackling emissions from DSM activities and shipping, it is important to note that it retains some degree of oversight of all forms of emissions. Particularly those general and more specific commitments made by States under the Paris Agreement will create strong political obligation to minimize GHG emissions from deep-sea mining.

7.2. The DSM regime

DSM activities involving the international seabed ('the Area') are regulated under Part XI of the United Nations Convention on the Law of the Sea 1982 (UNCLOS), an international treaty setting out various rights, responsibilities, and obligations for all activities in the Area. Article 136 of UNCLOS declares the Area and its mineral resources as the 'common heritage of mankind.' Essentially, this means that no states may exercise sovereignty in the Area and that the mineral resources and benefits derived from their exploitation can only be administered through a dedicated international organization. The International Seabed Authority (ISA) was established under Article 156 of UNCLOS with the mandate to design a regime to regulate DSM activities in the Area. The ISA has issued 30 exploration licenses in the Area (as of July 2019) and is currently at an advanced stage of developing regulations to govern exploitation activities (Mining Code). This effectively means that exploitation activities could, from a regulatory perspective, commence in the coming few years.

In designing regulations to develop the mineral resources in the Area, the ISA is required, pursuant to Article 145 of UNCLOS, to take necessary measures to ensure the effective protection of the marine environment from the harmful effects of DSM activities. However, even if interpreted broadly, it is unlikely that Article 145 has a climate protection objective (i.e. that it aims at protecting the climate from GHG emissions resulting from DSM activities)[2].In this connection, it comes as little surprise that most of the present regulatory discourse focusses heavily on marine environmental protection objectives. Despite that, the ISA has taken progressive and opportune steps in considering all DSM-related activities at mining sites, including GHG emissions, to be under its purview. In this regard, GHGs and other chemical emissions are mentioned in the ISA's current Revised Draft Regulations on Exploitation of Mineral Resources in the Area (ISBA/25/ C/WP.1), specifically in Annex IV ('Environmental Impact Statement', under sections 4 ('Description of the physicochemical environment') and 7 ('Assessment of impacts in the physicochemical environment and proposed mitigation'). Even though the quantity of emissions does not appear to be a decisive factor in granting or reviewing an exploitation license, the ISA nevertheless re- quires contractors applying for an exploitation license to submit an estimation of on-site GHG emissions and their potential impacts on the environment in their environmental impact statement (EIS).

It is apparent, however, that the ISA does not include the transportation of the mineral ores from mining sites to onshore processing facilities in the assessment. Section 3 of Annex IV of the same document stipulates that: "While it is expected that this section would provide a brief description of the entire project, including offshore and land-based components, the EIS should focus on those activities occurring within the Authority's jurisdiction (e.g., activities related to the recovery of minerals from the Area up to the point of transshipment)" (48).

7.3. The international shipping regime

Recognizing that shipping is a transnational activity, the global community established the Intergovernmental Maritime Consultative Organization in 1948, later renamed as the International Maritime Organization (IMO) in the 1970s, to regulate and standardize shipping routes and rules of navigation. A series of incidents at sea, particularly oil pollution through accidents and spills, prompted the IMO to take immediate measures to protect the marine environment. This resulted, inter alia, in the conclusion of the International Convention for the Prevention of Pollution from Ships 1973/1978 (MARPOL) (49). The most important treaty provisions that address air pollution emissions from seagoing vessels are included in Annex VI of MARPOL, which was inserted in 1997. According to Article 3.1a and Art. 3.1b of MARPOL, the convention applies to all ships "flying the flag of a Party to the Convention" as well as those "not entitled to fly the flag of a Party but which operate under the authority of a

[2] For broad interpretations of Article 145, see (56). Note also that Article 212 (contained in Part XII of UNCLOS on the protection and preservation of the marine environment) emphasizes the "need for laws and regulations to prevent, reduce and control pollution of the marine environment from or through the atmosphere".

Party.” In principle, this includes vessels engaged in potential mining activities. However, Section 3.1 of Annex VI exempts those emissions directly arising from the exploration, exploitation and associated offshore processing of sea-bed mineral resources from the requirements of Annex VI (see section 3.1.1- 3.1.4 Annex VI MARPOL). Accordingly, only those operations that are not directly linked to the on-site mining activities, including, in particular, emissions resulting from vessels commuting to and from the mining sites, are subject to the regular environmental requirements laid down in MARPOL Annex VI. Annex VI regulates emissions of gases, predominantly of SO_X and NO_X. In 2011, the Annex was expanded to additionally include GHGs. Vessels receive Engine International Air Pollution (EIAPP) Certificates when complying with NO_X regulations established by MARPOL, and the NO_X Technical Code 2008 (MEPC.177(58)). There are currently three levels of NO_X control (‘Tiers’) depending firstly on the vessel's construction date and secondly on the engine's rated speed. The regulations are stricter for newer ships. MARPOL currently limits the sulfur content of fuel oils to 3.50% w/w (weight by weight). From 2020 onwards, the threshold will de- crease to 0.50% w/w. In designated emission control areas (ECAs), the sulfur limits are already at 0.10%. With reference to the case study described above, this would only affect a potential transport to Canada, as between 15% and 50% of the travel route would be located within a current ECA. In recent years, as a result of increasing pressure from the climate regime, the IMO's Marine Environment Protection Committee (MEPC) has also been trying to develop and negotiate international rules and standards to target GHG emissions from vessels. For instance, in April 2018, the MEPC adopted Resolution 304(72), entitled the ‘Initial IMO Strategy on Reduction of GHG Emissions from Ships’ with the ambition of reducing the total annual GHG emissions by at least 50% by 2050 compared to 2008. Before that, it had established some measures to increase the energy efficiency of ships, including the Energy Design Index (EEDI) and the Ship Energy Efficiency Plan (SEEP) (MEPC.203(62)). It is also committed to encouraging technical co-operation and technology transfer among member states in this area (MEPC.229(65)). In addition, the IMO encourages the voluntary use of the Ship Energy Efficiency Operational Indicator (EEOI) to assist ship owners and operators with the evaluation of their fleet concerning the reduction of CO_2 emissions (MEPC.1/Circ.684). Moreover, the IMO adopted resolution MEPC.278(70) which requires ships of 5000 gross tonnage to collect and report fuel oil consumption data to be stored in the IMO Ship Fuel Oil Consumption Database. As the IMO has started to occupy the field to regulate GHG emissions from ships, the designation of more progressive and specific regulations pertaining to this is anticipated.

8. Recommendations

Although the emissions caused by DSM operations in the CCZ will be considerably smaller than those of other maritime sectors such as international shipping, they should not be neglected, as their impacts add to already critical atmospheric GHG and pollution levels. As mining vessels do not fall under the remit of the IMO GHG and air pollution regulations, measures should be taken to minimize emissions, not only for the benefit of well-being of the environment and humankind, but also because fuel consumption, to which emissions are directly related, make up a substantial share of the mining endeavors' operational costs. Although the IMO's EEDI cannot directly be applied to stationary vessels, the use of energy-efficient engines can be recommended. Moreover, it may be possible to at least partially adopt the SEEP or a similar quality management tool to optimize processes onboard, as well as the logistical concepts and stakeholder cooperation. Moreover, al- though not demanded by the IMO or the ISA at this point, it may be possible to install abatement technology to reduce emissions of individual pollutants like NO_X and SO_X, or to consider the use of alter- native fuel sources. For instance, liquefied natural gas (LNG) reduces CO_2 emissions by 20–30%, NO_X emissions by 80–90%, and nearly all emissions of PM and SO_X, as LNG does not contain sulfur (20). To not diminish the benefits of using LNG, it is crucial to control methane slop, which occurs if CH_4 leave the engine unburnt. LNG infrastructure is, however, not widely available yet. For instance, Mexico currently has only three operational LNG terminals, two of which are located on the Pacific coast. New Fortress Energy, however, has recently been granted a long-term contract for building a new LNG import terminal at the Pacific coast in the Port of Pichilingue in Baja California (50). In Canada, there are 20 proposed LNG terminals, 14 of which will be located on the West coast (51). Nevertheless, LNG is considered a 'fuel of the future' and the fleet of vessels operating on LNG is constantly growing. Moreover, the sea-to-sea bunkering process for LNG is a current focus area of technology development in the international shipping sector. DNV GL, an international accredited registrar and classification society for ships and vessels, states that by 2020, between 400 and 600 LNG bunker vessels will operate globally (52). The choice of fuel, from an environmental, economic and technical point of view, already needs to be considered during the early planning stages of a commercial mining operation, as LNG requires twice the storage volume compared to HFO. Another alternative would be to operate on marine distillate oil (MDO) or marine gas oil (MGO). This would slightly increase the CO_2 but considerably decrease the SO_X and PM emissions, as the S content of the fuel is considerably lower in MDO/MGO than in HFO. In fact, vessels sailing within sulfur emission control areas (SECAs), which currently include the North and Baltic Seas as well as the North American coastlines and are characterized by particularly strict S emission levels, often switch to MDO/MGO upon entering these designated areas. Other vessels continue to operate on HFO but install exhaust gas recirculation systems (‘scrubbers’) (53). These systems remove SO_X and, to a certain degree, NO_X and particles from the vessels' exhaust gas. Scrubbers can operate as open or closed loop or hybrid systems. Open loop systems use seawater to clean the exhaust gas from pollutants and discharge the acidified effluent directly into the surface water. Closed loop systems re-circulate fresh water and buffer the acidified water with sodium hydroxide, resulting in the solid waste product calcium sulfate (‘gypsum’), which in turn has to be treated on land. Although scrubber technology presents a cost-effective solution to reducing SO_X emissions, it is often criticized for shifting the problem from the air to the water column. To date, relatively little is known about the composition and biological and biochemical consequences of discharging scrubber effluents (54). Research does, however, indicate that the use of open-loop systems may be associated with adverse environmental impacts including the accumulation of heavy metals in the marine environment and an increase in zooplankton mortality (55). This could be particularly problematic when used in a mining vessel, which would spend an extended period at a specific mine site and discharge the acidified effluent in the same location. The transport vessels fall under the remits of the IMO and need to comply with its increasingly strict regulations regarding the adoption of the EEDI and the SEEP, as well as the reduction of SO_X and NO_X. In addition, it may be possible to reduce emission by means of slow-steaming, i.e. speed reductions, or through the optimization of travel routes. However, as the vessels involved in the transportation of minerals will commute between the mine site and the destination ports on an ideal route, this measure would probably not be effective in the field of DSM. Similarly, slow-steaming is viewed critically in international shipping, as slower travel speeds result in the prolongation of the voyage, which decreases the impact of the measure. For example, a change in speed of the transport vessels from the CCZ to Mexico from 14.5 to 12 knots would only reduce emissions by a factor of 1.19 due to the increase in travel time of 0.62 days. If the travel time were to remain the same, the consumption would differ by a factor of 1.46. Overall, the contribution of the transport vessels (not including bunkering vessels or other support vessels) is considerably smaller than that of the mining vessel.

9. Conclusion

DSM will generate GHG emissions and air pollution, which will adversely affect ecosystems and human livelihoods. The exact magnitude of emissions is difficult to predict due to the unavailability and inaccessibility of commercial or experimental-scale energy demand data. Therefore, we have based this assessment on energy demand estimates provided in three different reports by Ramboll & HWWI (17), McLellan (16), and Agarwal et al. (15) It is, however, important to note that it is at this stage difficult to determine which of these studies provides the most reliable demand estimates that best represent the energy demand of future commercial-scale nodule mining operations, and thus the emission levels presented here should be seen as a best estimate at this moment in time. In fact, the energy demand estimates provided in the three studies are vastly different, which is most likely related to different assumptions regarding the technical specifications of the mining equipment and mining vessels. However, the varying degree of detail with respect to the description of the technological assumptions and the partially missing references for the energy demand of individual equipment pieces makes it difficult to clearly evaluate these differences.

In the light of cumulative impacts of anthropogenic GHG emissions and air pollution, there is a need to minimize emissions levels, even if the exact quantity of emissions remains uncertain at this point. We would therefore like to emphasize the urgent need to integrate emissions from DSM into the regulatory regimes concerned with climate change, air pollution and shipping. Specifically, we propose that the ISA and the IMO should strengthen their cooperation to consider the im- plications that DSM would have in relation to GHG emissions and clarify issues of potentially overlapping mandates. In this regard, there is an Agreement of Cooperation between the IMO and the ISA, concluded in 2016, that already provides a platform for further consultation, collaboration, and coordination (see https://www.isa.org.jm/files/documents/EN/Regs/IMO.pdf). Addressing this gap would ensure that fuel consumption and GHG emissions during mining activities are appropriately accounted for from a policy perspective. With respect to technical measures, the use of energy-efficient engines and generators, as well as the use of alternative fuels like LNG or the installation of abatement technology should be considered to reduce emissions – even though this is not required by current regulation.

Overall, many factors will influence the levels of GHG emissions and air pollution of a commercial-nodule mining operation, such as the annual production of the mining operation, the technological specifications of the mining vessel and equipment, the engines installed on the mining and transport vessels, the specific fuel oil consumption of these engines, the bunker and storage capacity of the vessels, the transport distance and speed of the transport vessels, and the time spent in different operational modes. It is, therefore, necessary to continuously update and refine the assessment of GHG emissions and air pollution, once planning advances and more detailed data becomes available. Reducing emissions is not only of interest from an environmental or sustainability-related point of view but may also be of relevance from an economic perspective as fuel consumption, which is the predominant cause of emissions, makes up a considerable share of the flexible cost of a mining operation. We suggest the use of the methodology presented here for the future quantification of DSM-related air pollution and GHG emissions.

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