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Jean-Baptiste Bahers, Paula Higuera, Anne Ventura, Nicolas Antheaume. The “Metal-Energy-Construction Mineral” Nexus in the Island Metabolism: The Case of the Extractive Economy of New Caledonia. *Sustainability*, 2020, 12 (6), pp.2191. 10.3390/su12062191 . hal-02507504

HAL Id: hal-02507504

<https://hal.science/hal-02507504v1>

Submitted on 1 Jun 2022

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Article

The “Metal-Energy-Construction Mineral” Nexus in the Island Metabolism: The Case of the Extractive Economy of New Caledonia

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Received: 16 January 2020; Accepted: 5 March 2020; Published: 12 March 2020



Abstract: The concept of island metabolism strives to implement the principles of social ecology at the island scale. It is, therefore, a question of analyzing the flows of materials and energy passing through these territories, as well as the resource base needed to sustain their activities. We propose to develop a nexus approach to the New Caledonian island metabolism to understand the interactions between biophysical structures and societal, as well as economic, activities. Metals, construction minerals, and energy are good symbols of economies based on the extraction of non-renewable resources. This is why, in this article, we sought to investigate how the “metal-energy-construction mineral” nexus can affect the resilience and metabolic sustainability of the extractive island of New Caledonia. We carried out the Material and Energy Flow Analysis (MEFA) of each nexus subsystem for 2016 and of the nodes of interdependence. We also interrogated the role of importing countries because the island’s metabolism is dominated by the nickel extraction industry. Indeed, the metabolic profile of this island corresponds to the one of a supply territory for other consumption territories. The latter outsource the impacts of their own consumption to New Caledonia. Finally, based on interviews with economic stakeholders, we studied the potential building blocks for the emergence of an industrial symbiosis in the nexus.

Keywords: island metabolism; MFA; nexus approach; industrial waste; metabolic profile

1. Introduction

1.1. Research on the Metabolism of Islands: What Resilience and Sustainability for These Territories

The concept of island metabolism strives to implement the principles of social ecology [1,2] at the island level. It is, therefore, a question of analyzing the flows of materials and energy, which pass through these territories and the resource base needed to sustain their activities. Methodologies to measure material and energy balances have been developed, in which metabolic indicators are used, derived from material flow analysis (MFA), such as Domestic Material Consumption (DMC), Net Addition to Stock (NAS), or Domestic Process Outputs (DPO), among others. These indicators are often combined with economic indicators to reveal the efficiency of productive systems and consumption

patterns. Pioneer work has been carried out on the islands of Iceland, Trinidad, Grenada, or Samothraki in Greece [3–7] that has enabled, in very different contexts, us to understand the metabolic profiles of these islands and to describe the perspectives for local sustainability. Comparing resource consumption and the evolution of the gross domestic product (GDP) over a long period of time is also an expected objective of this research field, such as in the work of Martinico-Perez et al. [8], who conducted a study of the socio-economic metabolism of the Philippine archipelago, in order to understand the evolution of island environmental pressures.

Additionally, other scholars, especially in the field of industrial ecology, have taken an interest in island metabolism. These researchers produced analysis and recommendations towards the implementation of industrial synergies, defined as the exchange of co-products or waste between economic actors [9,10]. Political ecology has, in turn, provided specific studies to link the biophysical properties of islands with their social and geopolitical characteristics. Thus, the collapse of ecological environments related to water or forest resources [11,12] and the environmental consequences of industrial activities, such as tourism [13], mines [14], or extraction of fossil fuels [15], have been studied. Finally, a French school of thought denominating itself as “territorial ecology” [16] proposes the notion of territorial metabolism, in view of establishing methodological links between flow analysis and their modes of spatial governance, as well as the social and environmental consequences of material circulation.

These various approaches of island metabolism make it possible to understand how these territories depend on the exploitation of natural resources exported to world markets. Their economic apparatus is structured around types of exploitation: such as extracting minerals, fossil fuels or water from below ground deposits, or using aboveground vegetation. These activities lead to excessive production of waste in relation to the number of inhabitants, as will be further detailed in the next section. Furthermore, some islands export most of their production and import almost all of their food, energy, or material needs [3]. These economic and power relations between mining territories and importing areas [17] perfectly illustrate the context of the metabolic relationships of islands with the rest of the world and highlight metabolic vulnerabilities.

Issues related to economic and environmental resilience thus appear to be essential to enable small islands, considered as life-size laboratories for methodological and political experimentation, to be more sustainable and more self-sufficient. Reducing these vulnerabilities is a considerable challenge and involves evaluating local energy or bioeconomic policies, as previously analyzed in the Galápagos Islands [18] and the Balearic Islands [19]. The perspective of resource efficiency is therefore an essential alternative in these extractive economies to possibly reduce the metabolic vulnerabilities of these islands [20] and to analyze if a new circulation of materials can reduce existing unbalances and weaknesses in the socioeconomic metabolism.

1.2. The “Metal-Energy-Construction Mineral” Nexus

Social and island metabolism are essentially linked to the nexus of resources, that is to say, the “links between different forms of interdependent uses of resources as well as the institutional settings and broader societal conditions under which they occur” [21]. With a nexus approach, resources that enable the functioning of human societies are not analyzed as silos but, on the contrary, as interactions between biophysical structures and societal organization. It is thus necessary to acknowledge that the use of a resource is dependent on the mobilization of other flows of material and energy in connection with a social structure. In addition, the integration of a “nexus-thinking” analysis shows the importance of combining several methodological approaches, as indicated in the review of Newell et al. [22]. Indeed, a modeling approach, such as MFA, is essential to measure the socio-economic metabolism of territories [2,23] and to understand the evolution of consumption indicators and resource demands. These flows are interdependent and require a complex analysis of their material dynamics. However, we cannot just quantify flows without a socio-political approach integrating these concepts with institutional, economic and social actors. Albrecht et al. [24] demonstrate the need for mixed and

transdisciplinary approaches that integrate the socio-economic and political dimensions of resources, as well as involve stakeholders and policy-makers.

Many reviews have been produced on the concept of nexus, as a new scientific buzzword. They mainly concern the water-energy-food (WEF) nexus [24–27]. However, existing research did not study territorial issues, beyond administrative perimeters. The work of Newell et al. [22] partially fills this gap for urban areas. In particular, their article concludes that the multi-scalar, institutional, and governance aspects are little discussed in the WEF nexus literature, unlike quantitative and modeling approaches. Other research has already shown the strong conceptual links between urban metabolism and nexus [28–30]. The results obtained are a basis for questioning resource use from a political and social point of view in urban areas.

In addition, a majority of studies focus on the WEF nexus, whereas many other nexus could have been studied [21,30,31]. To our knowledge, the links between the flows of metals, building construction minerals, and energy have never been addressed, despite being three of the main flows of social metabolism. Metal slags are common wastes of all extraction activities, which have historically led to drastic changes in landscapes in the past century, forming hills, such as the famous ones called “*crassiers*” for iron ore extraction in the East of France or “*terrils*” for hard coal mining in the North of France. In the last years of the 20th century, it was progressively discovered that some of these waste hills contributed to soil and water pollution but also that they were composed of interesting minerals. Today, *crassiers* no longer grow because iron slags are very popular and important added value products for the cement industry. This illustrates how the links between the three “metal-energy-construction mineral” sectors operate. Moreover, they are three categories of resources that are economically critical and are likely to have reached their production peak [32]. Finally, metals, construction minerals, and energy are a good symbol of economies based on the extraction of non-renewable resources [33], as are some islands [34]. This is why, in this article, we seek to investigate how the “metal-energy-construction mineral” nexus can affect the resilience and metabolic sustainability of an extractive island.

2. Case Study: The Island Metabolism of New Caledonia

Our investigation is entirely in line with the case of the New Caledonian archipelago. The extraction and production of nickel forms a large part of the socio-economic metabolism of the island, as this industry is a major part of the economy. In addition, the transformation processes (hydrometallurgy and pyrometallurgy) discharge huge amounts of ferronickel slags, greenhouse gases, and wet residues (for the hydrometallurgical process). Today, nickel slags are sometimes locally used as road embankments, and some projects seek solutions to turn them into building materials (see Section 4.3).

The mining and metallurgical sector accounts for 14% of employment in New Caledonia [35], half of which is direct employment (mining, metallurgy) and the other half subcontracting, construction, transport, or associated services. The nickel sector is responsible for the majority of exports. The economic footprint of nickel extraction does not stop with extractive and metallurgical activities because this sector also has a ripple effect on the rest of the economy through its use of subcontracting and the consumption of its employees. Today, nickel is used for batteries, coins, hygienic packaging (especially food), and especially for making non-corrosive alloys or superalloys in all industrial sectors, such as the automotive industry, aviation, or chemistry.

New Caledonia was the world’s sixth-largest producer of nickel in 2014, and its reserves are considerable: 15% of the global total identified to date [35]. The main forms of nickel ores are of two types: sulfide ores and oxidized ores. Nickel in sulfide ores accounts for 65% of global production and is mined underground. Nickel from oxidized ores, found in New Caledonia, accounts for 35% of world production.

The mining area is well distributed over the whole of “*Grande Terre*” and the “*Belep Islands*” (cf. Figure 1). Mineral extraction is based on mining concessions, either directly operated by the mining branches of metalworkers, or by “minor miners”, who own a domain, as well as export licenses. The ore, which is processed locally, is distributed between three metallurgical sites:

- The “Société Le Nickel” (SLN) plant: its capital is 56% owned by Eramet (French industrial company), 34% by STCP (Provinces of New Caledonia), and 10% by Nisshin Steel (stainless steel producer in Japan). It uses a pyrometallurgical process and produces ferronickel. It is the oldest corporation on the island.
- The “Koniambo Nickel SAS” plant processes high-grade saprolites from the Koniambo mountain in the North Province using a pyrometallurgical process. Its capital is 51% owned by the South Pacific Mining Corporation (SMSP) (itself owned by the North Province), and the remaining 49% was recently acquired by Glencore (British-Swiss company), which purchases all the ferronickel that is produced by this plant. The plant went into production in 2013. It is considered as a political “instrument” for the emancipation of native indigenous populations (Kanaks) from France [36].
- In 2010, the “Vale Inco” hydrometallurgical plant started its operations. It is 95% owned by a private international consortium (including the Brazilian company Vale), and the remaining 5% is held by the Southern and Northern Provinces.

Another major player in mining is the Nickel Mining Company SAS, which operates several mining centers to supply the ferronickel production plant in Gwangyang (South Korea). This South Korean pyrometallurgical plant, which began operations in 2008, has an annual production capacity of 30,000 tons of ferronickel.

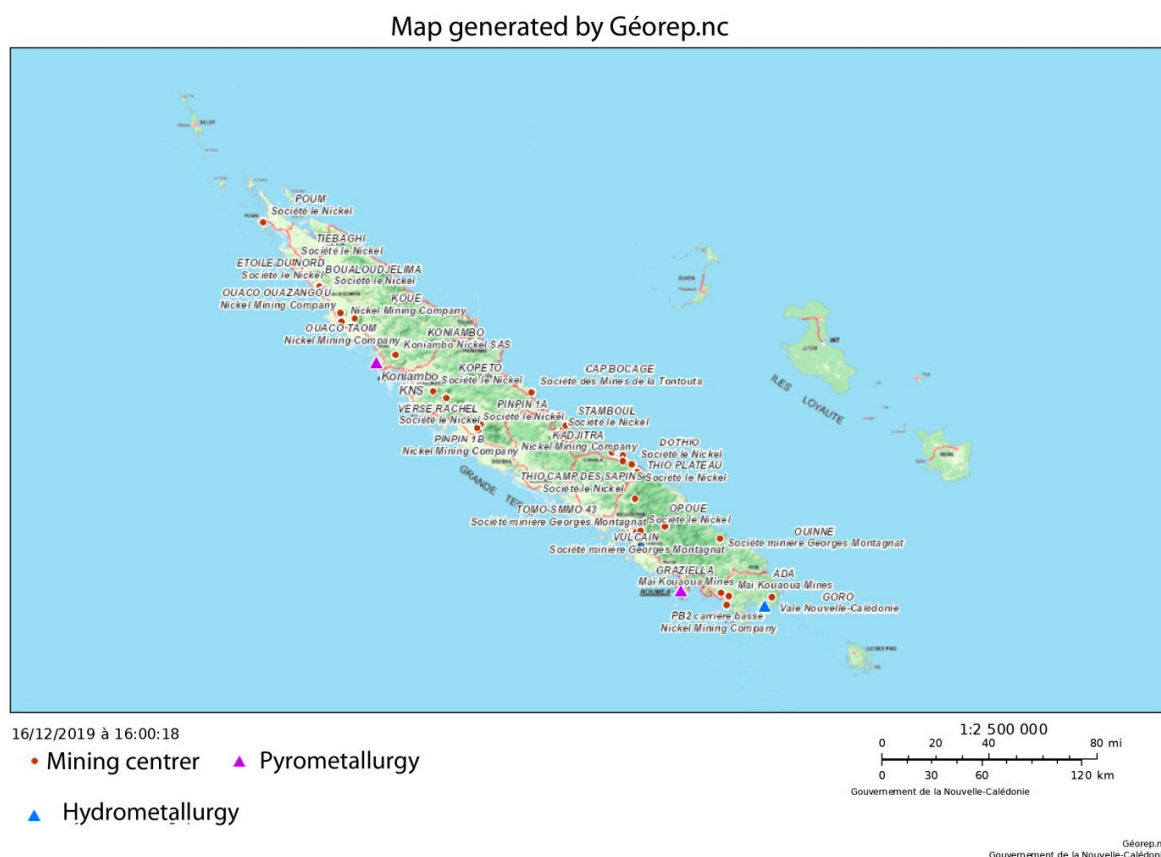


Figure 1. The mining and metallurgical centers of New Caledonia (Data - *Gouvernement de la Nouvelle-Calédonie – creative commons licence*).

Extractive economies do not go without conflicts over the associated social metabolism, [37–39], and the case of nickel extraction in New Caledonia is no exception: it is not without conflict or socio-environmental controversy. If this sector employs many workers, the relationship of islanders with nickel is delicate. For example, it is known that the Kanaks call it “the shit” [40]. Since the 2000s, the “*Rhéebù Nùù*” Committee and the Native Council for the Management of Natural Resources

in Kanaky New Caledonia were opposed to the launch of the Vale Inco project (formerly named Goro-Nickel) [41]. This conflict is related to pollution from extraction, such as in Thio [42], and to sulfuric acid spills in rivers in 2009, 2012, and 2014 by Vale Inco [43]. Some organizations were created, such as the “CEIL” (Observatory of the environment in New Caledonia) in 2009, the mission of which is to protect the environment. This mission is shared between different categories of stakeholders [43]. More recently, a socio-economic conflict affected the exploitation of nickel. In 2015, mine truckers, allied to the miners, opposed the local government’s ban on exporting nickel ore to China [44]. This ban took place in the context of falling world prices and tough negotiations with existing Australian customers, wishing to revise existing contracts and push their advantage in a drastic way.

3. Method: MFA for the Nexus from International Local Data and Interviews

3.1. At the Level of the Island Flows

Many methods exist for modeling resources nexus in order to analyze the sustainability of territories [31], such as the Biogeophysical model, Life Cycle Assessment or Cost – Benefit analysis. We chose MFA to assess the trajectory of intra and extra-island flows by quantifying them, but also by spatializing them. This method also makes it possible to characterize stocks and material consumption by measuring flows of materials and energy entering the island, which are transformed and disposed of [45–47]. In addition, previous research has demonstrated the value of using MFA to understand resources nexus [21,48].

We first set up a Eurostat MFA [49,50] to gather some data and obtain metabolic indicators comparable with other islands [3,20,51]. Hence, we were able to discuss socioeconomic metabolism in this territorial context in relation to indicators of the DMC such as unused extraction, domestic processing output (DPO) and addition to the stock (NAS). The metabolic profile of the archipelago is therefore very unique and highlights what these extractive economies are. They are a real supply base for other economies, with flows associated to exports.

3.2. At the Nexus Scale

We focused on the three sectors, studied as three subsystems. A large part of the data from the previous step was broken down by each sector, but the system boundaries of the MEFA (Material and Energy Flow Analysis) are very different from the Eurostat MFA, as we define our own system boundaries in Figure 2. Each subsystem can be considered as a MEFA based on the chain of resources [48,52,53], from resource extraction to end of life, including import, distribution, consumption, and export stages. The system boundaries, as defined in Figure 2, highlight what processes occur in New Caledonia. Hence, extraction and waste collection, which includes final disposal in New Caledonia, are considered to be inside the system boundaries. Process consumption is not comparable to the Eurostat DMC because it is a step of the chain and not an indicator. We then translated the concept of interdependencies as links between the sectors (cf. Figure 2), at different stages. Table 1 describes the primary data used for Figure 2 and the indicators discussed in Section 4.2.

A discussion of uncertainties is necessary to understand the material flow analysis. First of all, the majority of the sources come from local databases (Customs Office, Input-Output table, Import-export statistical studies, and environmental energy). They come either from the statistical institute of New Caledonia (ISEE) or from the governmental service for industry, mines, and energy (DIMENC). These data are subject to uncertainties, such as statistical variation and spatio-temporal variability [54]. They also come from questionnaires sent to companies, which certainly have the obligation to complete them but are subject to random checks only. These uncertainties are described as “measurement errors” by Patricio and colleagues [55] because these data are collected by the institutions providing the databases. Finally, they do not take into account *free riders* or informal sectors, which can be important in island metabolism [20]. This type of uncertainty is “aleatory” [54], which means that it results from randomness and that the variability cannot be reduced. As regards

data from the interviews, they are dependent on the “subjective judgment” of economic actors [54]. Yet, we cross-checked these data with the principle of mass balance for the MFA, which provides the verification of tendency. This is an “epistemic” uncertainty [54], meaning a lack of knowledge, which is minimized through cross-examination. To improve the accuracy of the results, we carried out a temporal analysis, inspired by dynamic material flow analysis [56], in order to see the evolution of flow data and metabolic indicators (see Section 4.2).”

Table 1. Source and processing of data for the material flow analysis.

PRIMARY DATA for Figure 2	Source	Year of Data	Types of Processing
Metals extraction	USGS ***	2001–2016	None
Unused extraction	Interviews with economic stakeholders	2016	This data is verified with USGS-ISEE ** (difference between extraction and exports)
Metallurgical process	ISEE - Input-Output table of New Caledonia economy	2016	None
Metals Waste collection	Interviews with economic stakeholders	2016	Ratios from interviews and inputs of metals processing
Metals exportation	ISEE ** - Customs Office of New Caledonia	2001–2016	None
Import of fossil fuels	ISEE ** – Energy Environment	2001–2016	None
Energy transformation	DIMENC * Government of New Caledonia : Energy transition diagnostic and planning	2015	Estimate based on ISEE ** data (10% increase of imports)
Energy distribution	ISEE ** – Energy Environment	2016	
Energy consumption	DIMENC * Government of New Caledonia : Energy transition diagnostic and planning	2015	Estimate based on ISEE ** data (10% increase of imports)
Energy losses	DIMENC * Government of New Caledonia : Energy transition diagnostic and planning	2015	Estimate based on ISEE ** data (10% increase of imports)
Atmospheric emissions	DIMENC * Government of New Caledonia : Energy transition diagnostic and planning	2015	Estimate based on ISEE ** data (10% increase of imports)
Imports of minerals	ISEE ** - Customs Office of New Caledonia	2001–2016	None
Minerals extraction	DIMENC * Government of New Caledonia :	2007; 2016	None
Minerals transformation	ISEE ** - Input-Output table of New Caledonia economy	2016	None
Cement consumption	ISEE ** - Input-Output table of New Caledonia economy	2001–2016	
Minerals consumption	ISEE ** - Input-Output table of New Caledonia economy	2016	None
Minerals waste collection	Report from Jouanny, 2016	2016	None
INDICATORS for Section 4.2			
DMI = imports (<i>biomass, minerals, fossil fuels, manufactured products, metals, chemicals</i>) + extraction (<i>biomass, minerals, nickel, cobalt</i>)	For imports: ISEE ** - Customs Office of New Caledonia For extraction: DIMENC * & USGS ***	2001–2016 (2017) 2016	Data for mineral import in 2016 is exceptionally high (+160% of 2015 and 2017). To avoid the effect of an unrepresentative year, we chose 2017 for this data.
DMC = DMI – exports (<i>nickel, cobalt, , fisheries</i>)	For exports: ISEE ** - Customs Office of New Caledonia	2016	
DPO = atmospheric emission + exported waste	DIMENC *, ISEE ** Energy Environment	2015, 2016	Estimate based on ISEE ** data (10% increase of imports)

Notes: * DIMENC = New Caledonian government department for industry, mines, and energy; ** ISEE = New Caledonian Institute of Statistics and Economic Studies; *** USGS = United States Geological Survey.

Thus, the “metals” subsystem focuses on nickel from its extraction to its export. The spatial trajectory of export is also studied. Hydrometallurgy and pyrometallurgy are both considered. Hydrometallurgy consists of treating the ore by leaching, which is to say by means of a solvent under

pressure in order to isolate the nickel. The solution contains dissolved metals but also solid residues, which are then removed by decantation. In the pyrometallurgical process, the ore is successively ground, pre-dried, calcinated, and reduced by fusion in high-power electric furnaces to decant the raw ferronickel. It is sunk and separated by gravity from the slag. The molten slag from the metallurgical process is cooled and fragmented by a curtain of seawater or poured on a slope to form a "flow", which cools in the open air. We decided not to separate these two processes in the MEFA in order to avoid too complex a representation. Thus, the sector is taken as a whole, in connection with the energy sectors and construction minerals. Furthermore, if the "water" sector is not considered in this research, since it is neither highly preponderant nor essential for the functioning of the nickel industry, it nevertheless remains a significant flow in island metabolism.

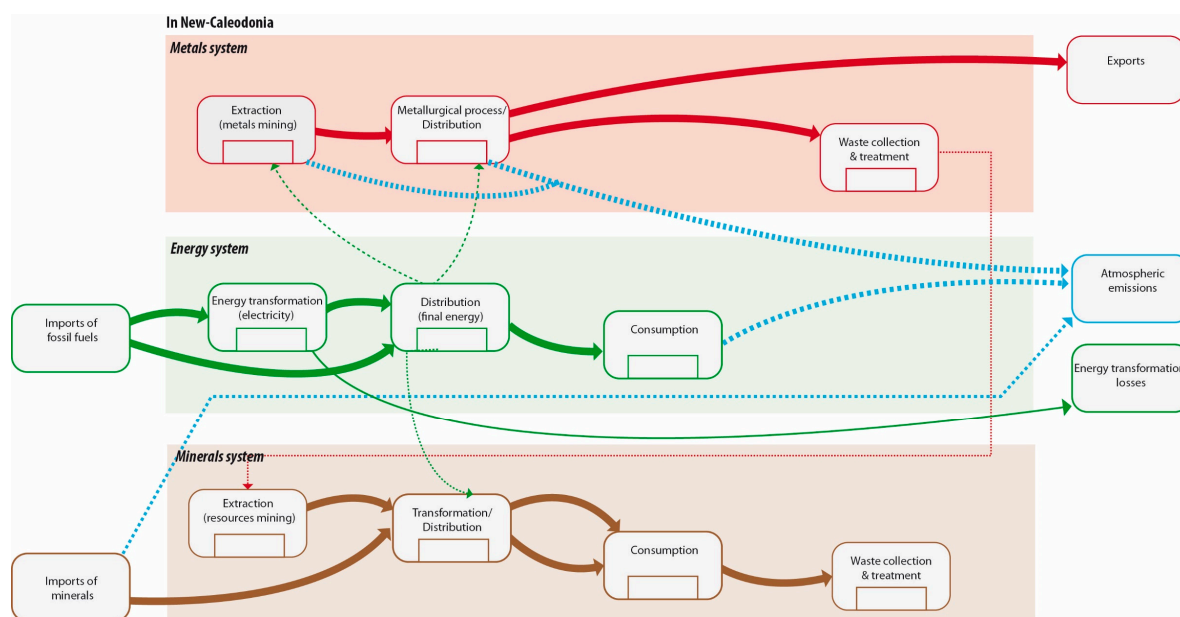


Figure 2. The metal-energy-construction mineral system studied.

Given the high-energy demand of the metal industry processes, the nickel-processing industry "energy" subsystem makes up most of the island's "energy" subsystem. Next to each metallurgical plant is a fossil fuel power plant. Fossil resources are imported from other parts of the world. Consequently, the greenhouse gas emissions of the subsystem are very significant.

The "construction minerals" subsystem sets out to describe the construction and building sector. There is only one cement company on the island, which imports its raw materials. Some other minerals, such as basalt, sand, and stones, are extracted in New Caledonia. Construction minerals are essential to the nickel sector for the construction of metallurgical plants. The strong development of the nickel industry in the 2010s led to a strong growth of construction activities. The analysis of the flows related to the construction minerals sector is a basis for investigating the recovery of nickel slags as a substitute for other materials used in the construction industry. Indeed, there are several technological projects which aim to produce construction mineral products with a market value, from nickel slags, targeting New Caledonian and international markets (mainly in the Asia-Pacific region). Moreover, a small part of the slags is already used for backfilling, especially for roads and sometimes informally, by the inhabitants of the archipelago.

3.3. Field Survey with Island Stakeholders

We carried out a field survey on the archipelago to obtain more detailed data from island stakeholders. Semi-structured interviews [17,57] with key stakeholders were carried out on July 2019. The main themes of the interviews were:

- What are the missions of the stakeholder and his professional network?
- What is the economic structure of the different sectors, and what infrastructure projects are planned?
- How is the supply of materials organized, and what are the main challenges to come?
- How are the environmental, social, and spatial challenges of construction projects taken into account? What are the sticking points and conflicts?

We chose to carry out these interviews with the widest possible range of stakeholders:

- The director of a company in the concrete sector
- An environmental inspector from the environment department of the South Province
- The managing director of a recycling company (which uses plastic waste and slag to make paving stones and curbs)
- The CEO of a professional federation of quarry operators and mining companies
- The managing director of a company in the construction sector
- The representative of the federation of processing industries
- The Head of Technical Studies and Investigation Department of KNS
- The HSEQR (Safety-Environment-Quality) director of SLN

These semi-structured interviews allowed us to reduce the blind spots of local databases, in particular on unused extraction and on the quantities of slag from the nickel industry and their accumulation (see Table 1), on the management of some construction waste and the consumption of construction materials related to major infrastructure projects. There is a gap between the year of the interviews and that of the data collection. However, these interviews allowed us to capture the state of knowledge of stakeholders for a reference year because we warned them that we were working on the 2016 data. This implies asking them for an order of magnitude for this reference year. We also discussed the difficulties and constraints, as well as the levers and opportunities, for the emergence of new synergies in this "metal-energy-construction mineral" nexus. Unfortunately, some essential stakeholders were unable to receive us, such as the cement transformation company. This represents a limitation of our work.

4. Results: The Metabolic Nexus, the Material Footprint of the Island, and Obstacles for the Transition to an Industrial Symbiosis

4.1. The Metabolic Flows of the "Metal-Energy-Construction Mineral" Nexus in New Caledonia

Figure 3 summarizes the results of the MEFA in each nexus subsystem for 2016. The sectors are structured very differently and it should be noted that some operations are absent from the subsystems: there are no imports, and there is no consumption in the "metals" subsystem, and almost no local energy extraction (for convenience of representation, we have not integrated the 0.033 kt petrol equivalent of primary electrical production through biomass, hydraulics, and wind, which represents 2% of consumption).

The "metals" subsystem illustrates the profile of an extractive island with a considerable nickel production but also cobalt and chromium, which are taken into account in the study. However, nickel represents 98% of the extraction of metals. The imported metal flows, which concern 1.4% of imports (0.0054 million t), are considered as not significant in the subsystem. More than 15 million tons of minerals are extracted from New Caledonian soil. This figure has doubled since 2000 [58,59]. This corresponds to exports of 3.1 million tons in 2002 (cf. Table 1) and 5.8 million tons of nickel and ferronickels in 2016 [60]. The remaining mass concerns the solid and liquid waste streams, which are therefore greater than those of exported nickel ores and ferronickels. Thus, according to interviews with industrial stakeholders, 9.5 million tons of unused extraction materials are produced yearly and are stored on the island. This represents an annual addition to the stock of almost 10 million tons.

Actually, the stakeholders interviewed mention a ratio of 1.25 tons of liquid waste per ton of extracted ore in the case of hydrometallurgy, which results in a production of 6671 ktons/year; and a ratio of 14 tons of slag per ton of ore in the case of pyrometallurgy, which is equivalent to 2900 ktons/year. These "wasted" amounts, which one might call "negative returns", are far from negligible. However, to date, no measurements have been carried out, using a systematic and formal method, which could allow for their monitoring. As for liquid waste from hydrometallurgy, which consists of water, solvents, and inert waste, it is difficult to estimate the stock because part of the water is returned to the sea, not without causing pollution and controversies (see above). As regards slags, mainly composed of silica and magnesium oxides, the industrial stakeholders we interviewed estimate the stock to be in the range of 20 to 25 million m³, which is an overwhelming order of magnitude for such a small island. This result raises questions, presented in the following sections, about who is responsible for the dynamics of this production and what are the obstacles to the emergence of recovery streams.

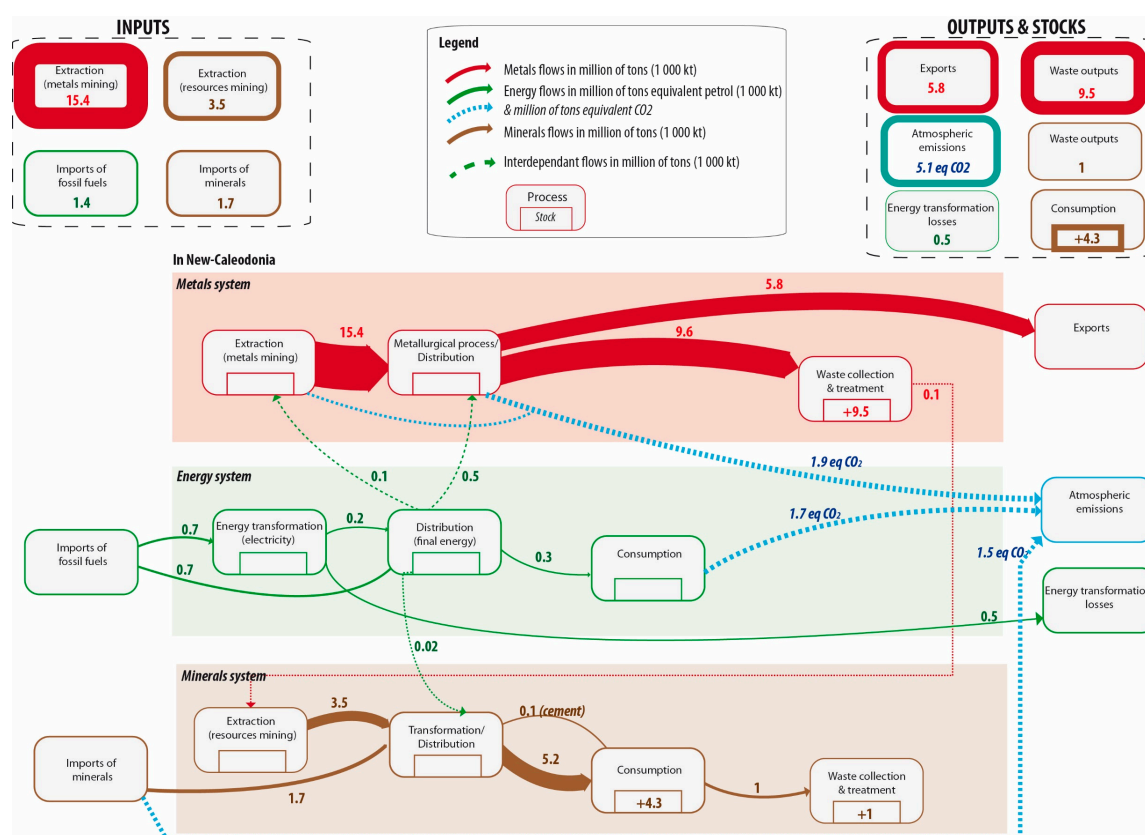


Figure 3. Results of mineral flow analysis (MFA) on the studied nexus.

The "energy" sector is very dependent on imports, growing from 0.65 million tons in 2000 to 1.56 million tons in 2016. This translates into an extremely low energy independence rate of 2.7% in 2016, which has not changed much since 2000 [61]. In addition, fossil fuels are the major source of energy with 63% of petroleum products and 34% of coal. A significant part is transformed into electricity by power plants, which were presented in Figure 3 as a loss of −0.5 million in the transformation process. Transport related to nickel concerns the majority of fossil fuel consumption with 0.2 million tons of petroleum products out of the 0.3 indicated in the consumption stage [62]. Despite investment programs in renewable energies and an increase in their production, it is clear that the energy balance is dependent on imported fossil fuels, which reinforces other economic imbalances.

As regards the construction minerals sector, it is also worth noticing the predominant role of imports—by boat—of these resources, which has increased a lot in recent years (from 0.18 million tons in 2009 to 1.7 in 2017). They account for 33% of material inflows [60], showing an additional dependence on other territories, although a significant fraction of minerals is also extracted locally, in particular basalt and sand, from 10 large quarries on the island [62]. Only one company produces cement, by mixing imported clinker with other components (recycled waste among others). The production of cement has decreased after reaching a consumption peak in 2010 (cf. Figure 4). However, since clinker is imported, and not made locally, this company is not considered as a cement plant. Clinker is imported from other countries, or even from other continents. In addition, there is not a single inert waste treatment facility in New Caledonia, although a constant flow of construction waste is used for damming in the Koutio-Koueta Bay, according to previous studies [63]. There are also unauthorized landfills on the island, making it very difficult to estimate both the flows and the stocks of inert waste.

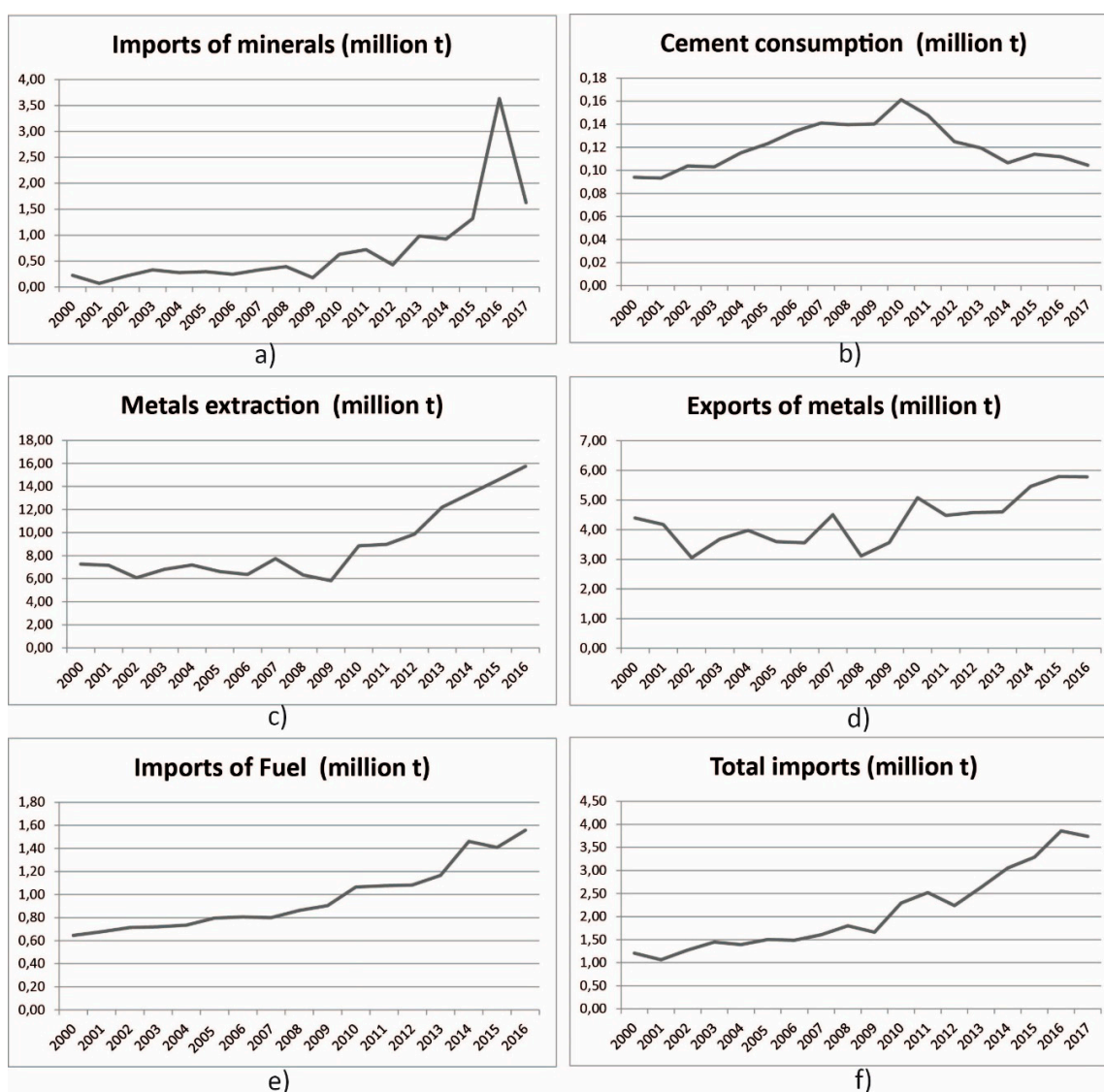


Figure 4. Temporal evolution of indicators (2000–2016). (a): Evolution of imports of minerals (million t); (b): Evolution of cement consumption (million t); (c): Evolution of metals extraction (million t); (d): Evolution of exports of metals (million t); (e): Evolution of imports of fuel (million t); (f): Evolution of total imports (million t)

Dashed arrows indicate the nodes of interdependence. They represent inter-system flows, from the processes of one system to the processes of another system, such as referred in Reference [48]. Thus, these flows do not contribute to the mass balance when they are not of the same color. They correspond to indirect flows in connection between two operations (with different colors). Some energy-related flows correspond to this case. The nodes of interdependence between the three subsystems are of four types. The “metals” subsystem is a very large consumer of energy, imported into the archipelago. This is the first preponderant node of this nexus. The metal sector is very dependent on energy. Indeed, 0.6 million tons of fossil fuels are distributed into the archipelago just for extraction and metallurgy [62]. This corresponds to 66% of total island energy consumption [61]. Thus, energy needs are distributed in a very unequal manner, which gives a very singular island context. The weight of this sector has a strong impact on socioeconomic metabolism. Consequently, the metals subsystem is a very strong producer of greenhouse gases (52% of direct island emissions, of which 47.8% for the metallurgical industry, and 4.2% for extraction in mines [62]). Therefore, the energy sector is closely linked to the metallurgical industry. The second node concerns the energy needs of the “minerals” sector. According to the Observatory of energy [62], the consumption of the construction industry is estimated at 0.02 million tons of mainly petroleum products. This flow is not predominant in the island’s metabolism. The third node concerns indirect emissions related to the import of mineral products. The latter represent around 47% of materials imports, an amount which has increased a lot since 2009 [60]. Indirect emissions of minerals imports, which stand at 1.5 million tons of CO₂, come from manufacturing in other countries and from distribution to the archipelago [62]. Even if these emissions do not occur directly in New Caledonia, they are induced by the consumption of mineral products on the island. According to the Observatory of energy [62], they are a major contributor to greenhouse gas emissions and are of the same order of magnitude as the contribution of nickel production, which stands at around 1.9 million tons of CO₂. Even though we do not have precise data on this subject, it is important to note that a very significant part of the minerals consumed is used for the construction of nickel-related infrastructure, such as the metallurgical plants (recently in 2010–2012) and access roads to the mines. Finally, the last node is that of the informal recovery of nickel slag as fill. According to industrial stakeholders, between 5 and 10% of the annual slag production, representing around 150 ktons/year, is reused as a filling material for its draining properties. This is very little compared to the annual production of slag, but it suggests options for a more systematic recovery of slags and a solution to the accumulation of the existing stock.

4.2. Spatialization of Nexus: The Material Footprint of Islands

The study of the “metal-energy-construction mineral” nexus shows volumes of flows which are very high compared to the relatively small population of New Caledonia (around 269,000 inhabitants). If we refer to the MFA indicators from the Eurostat guide [64], as presented in Section 1.1, results are exorbitant. For example, in 2016, according to our calculations (cf. Table 1), the DMI (which corresponds to domestic extractions – without the unused extraction - and imports) and the DMC (which corresponds to DMI from which exports are subtracted) were equal, respectively, to 50.7 and 29.3 tons/capita. By comparison, in France material input and material consumption stand at around 14 and 11 tons/capita/year according to the Eurostat database [65]. That is to say, they are almost three times lower than in New Caledonia. However, the island’s metabolism is dominated by “unused extraction”, using the terms of the Eurostat method, designating excavated flows without a local economic function [64,66]. These correspond to 35.7 tons/capita. This “unused extraction” mainly comes from the extraction and production of nickel. Likewise, the DPO (which adds up the emissions to nature without controlled landfills) is very high (13.8 tons/capita). This is much more than for France where this figure stands at around 7.2 tons/capita). In the same way, DPO in New Caledonia mainly concerns atmospheric emissions linked to the metallurgical industries (7 tons/capita of CO₂ equivalent). Thus, the Nickel sector and its energy and material interdependencies are clearly preponderant in the socio-economic metabolism of New Caledonia.

It is also relevant to compare these indicators with those of the small islands that have already been studied [3,7,8,20]. The DMC in Iceland and in Trinidad are around 23 and 17 tons/capita/year, which is quite similar to New Caledonia (29.3 tons/capita/year). Most of the extraction is used for a production based on local resources which are then exported (aluminum and ferrosilicon in Iceland and petroleum in Trinidad). This results in high rates of energy use and waste from production. The DMI is still much higher in New Caledonia (50.7 tons/capita/year) than in Iceland (29.1 tons/capita/year) but equivalent to Trinidad (43.5 tons/capita/year). On the contrary, the Philippines [8] or Ndzuwani in the Comoros [20] have a very different metabolic profile with a low DMC (6 tons/capita/year in the Philippines and 1.4 tons/capita/year in Ndzuwani), even if the extraction and export of essential oils from Ylang are the main economic sectors of Ndzuwani and the export of metallic ore is important in the Philippines (but this country also has a comparatively larger population, which brings down the per-capita ratio).

When we simulate the DMI and DPO indicators without the nickel supply chain (which remains entirely hypothetical and comes with many methodological limits), we obtain completely different results and much more in line with consumption levels in France. Indeed, without nickel, the DMI and the DPO (which is the atmospheric emissions + exported waste without landfilled waste) would correspond to 46 and 49% of the island indicators, that is to say, 23.6 tons/capita and 6.7 tons/capita, respectively, which is much closer to the French indicators (12 tons/capita for the DMC and 11 tons/capita for the DPO).

However, we can wonder about who is responsible for such high values. Most of the nickel produced is not used for New Caledonian consumption. It is exported to China, South Korea, Japan, Taiwan, the EU, France, and Australia (see Figure 5). These countries are amongst the biggest consumers of nickel in the world. In that perspective, approximately half of New Caledonia's material footprint [67] is imputable to the consumption of these nickel-importing countries, which are therefore responsible at the end of the chain for these environmental impacts. In fact, according to the conceptual terms of socioeconomic metabolism [39,68,69], slags and a large part of energy resource and atmospheric emissions are the raw material equivalents (RME) that "capture consistently the amount of extracted material needed to produce a certain (set of) product(s)" [64]. This metabolic indicator is directly related to the consumption of nickel in China, South Korea, Japan, Taiwan, the EU, and France because it corresponds to flows of energy and building materials necessary throughout the supply chain to produce the goods ultimately consumed in a given area. They are very difficult to identify in studies on socio-economic metabolism because they are generally not accounted for in the importing countries. However, these issues have become very prominent in the scientific literature [25,70]. They provide food for thought on geo-strategic power relationships, as well as on their ensuing impact on the metabolic relationships between territories [17]. In conclusion, the metabolic profile of this island is that of a supply base for other consumption territories, which outsource the impacts of their own consumption to New Caledonia. This result is thus a means of fueling reflections on metabolic outsourcing and therefore on the ultimate responsibility for environmental impacts, notably through the field of political-industrial ecology [71,72].

There are other paradoxical points in New Caledonia: Although it is a supply base for other countries, this island territory is also very dependent on imports. Excluding mining, these imported flows (10.6 tons/capita) are of the same order of magnitude as local extraction and production (13 tons/capita). Imports not related to nickel therefore meet 44% of the material needs of the archipelago, which shows the low autonomy of New Caledonia. In addition, historical trends show a strong increase in these imports, since this indicator was of 5.6 tons/capita in 2000 and of 6.8 tons/capita in 2009, showing a weakening of the material autonomy of New Caledonia.

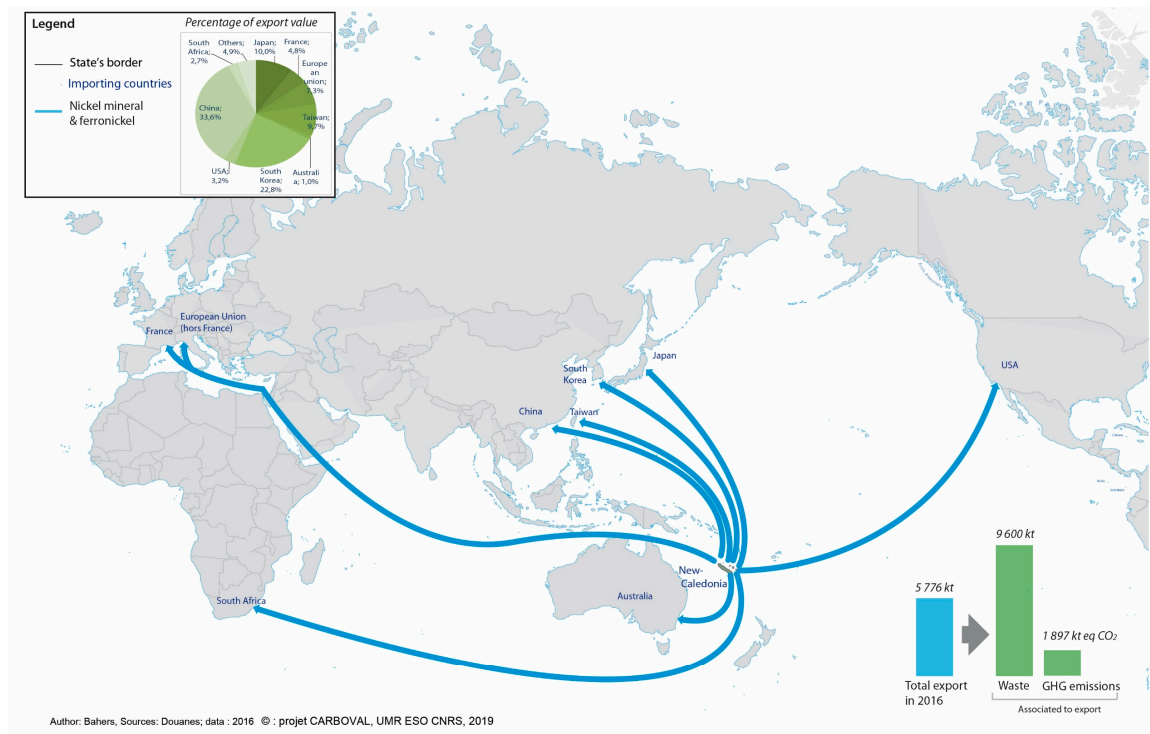


Figure 5. Destinations and amounts in 2016 of nickel exported from New Caledonia (Author: Bahers 2019).

4.3. Potential Building Blocks and Obstacles for the Emergence of an Industrial Symbiosis in the Nexus

According to pyrometallurgical companies in the territory, currently, metallurgical activities produce about 3 million tons of ferronickel slag per year in New Caledonia, out of 9.5 million tons of “unused extracted materials”. The chemical and mineralogical characteristics of ferronickel slag show an interesting potential for reuse as building materials, mainly due to the presence of SiO₂ and MgO (about 53% and 33%, respectively) [73]. This could lead to the development of an industrial symbiosis [9,74] between the nickel and construction sectors. Ferronickel slag can potentially replace part of the clay used in the manufacture of cement. It can also become a substitute to fine aggregates in the manufacture of concrete or be used as an aggregate for the manufacture of geopolymers and other types of cements [73]. The physiochemical properties of ferronickel slag, combined with the powers devolved to New Caledonia to define new construction standards, different from the French ones, should generate a strong interest for the recovery of this slag and give a second life to the construction sector. This could possibly reduce the import of mineral resources. However, today, this is not the case.

Indeed, when island stakeholders were interviewed we identified several obstacles. According to them, the current economic situation of the construction sector is not favorable. Since 2012, after the end of construction phases of the north and south metallurgic plants, the activity in the construction sector went substantially downwards. Concrete consumption has been decreasing since 2010, and production has been lowered by an average of 30% between 2010 and 2016. Consequently, the number of employees in this industry continues to decline: 1300 jobs could be destroyed in 2019, out of 6700 employees in total. Furthermore, for the economic and market forces of the construction sector, ferronickel slag is a material that may put the activity of the quarries currently in operation in New Caledonia at risk. Some stakeholders from the construction sector also express the idea that, today, there are also many important barriers (without specifying them more in depth) to the entry of new actors in the concrete market.

Other hurdles concern the possible construction materials themselves. Today, for concrete producers, there is no scientific evidence proving that ferronickel slags provide identical or better

performance for concrete compared to conventional cements or aggregates. Indeed, the mineralogical characteristics of ferronickel could generate an alkali-silica reaction and impair the strength of the concrete; this parameter is an important limitation in international construction standards, notably in Japan and Australia [73].

Finally, geographic isolation and the small size of the New Caledonian market will play an important role in any slag recovery strategy. According to the stakeholders concerned with local economic development, New Caledonia is a remote and poorly self-supplied territory, which generates high transportation costs. The availability of building materials is higher than the needs of the territory because of a small population. Any recovery option has to bet on foreign markets in order to export recovered ferronickel slag to the closest foreign markets, such as Japan, Australia, New Zealand, and the Pacific Community. In this case, it is important to consider foreign construction standards, their local policies concerning the use of metallurgic slag, and their political strategy as concerns local versus foreign sources of supply. According to a business manager we interviewed, exporting to the Pacific Community is not an obvious option. For example, although the Vanuatu archipelago does not have a geological bed that provides quality aggregates for construction, local and low-quality materials are preferred in order to maintain constructive independence.

These elements point out the difficulties of making the local construction industry evolve, mainly due to the structure of the market and to the island constraints of New Caledonia.

5. Conclusions

New Caledonia is currently facing important interconnected economic, resources, and environmental issues.

As Wiedman et al. mention: “Two fifths of all global raw materials were extracted and used just to enable exports of goods and services to other countries” [67]. As an extractive economy, it provides important nickel resources to the world. But far from ensuring flourishing economic perspectives through a positive trade balance, the situation increases its material dependency by requiring imports of huge amounts of energy resources in order to enable nickel production. Two thirds of local energy consumption, based mainly on imported fossil fuels, and half of CO₂ equivalent emissions are caused by the nickel production industry.

As an island, and although responsibilities can be attributed to nickel consuming countries, New Caledonia indirectly contributes to weakening its own position against the rise of sea level provoked by climate change, through its local emissions of greenhouse gases. The situation of the island also emphasizes the issue of land availability and local pollution considering the huge amounts of waste generated by nickel extraction and production. Indeed, we cannot neglect the wider environmental impacts of nickel mining in New Caledonia, which is in addition to being a very high greenhouse gas emitting industry, resulting in very significant land-use changes (from mines but also sedimentation of slags), acidification, and eco-toxicity, according to life cycle assessments studies [75,76]. A future in which the nickel reserves could be exhausted is not currently envisaged in New Caledonia because reserves are important. However, as shown by Mudd [77], the island could experience degrowth, forced by the depletion of fossil fuel resources and environmental cost constraints. This would further increase the economic and metabolic unbalances of the island. Furthermore, this situation will not eliminate local, long-term environmental impacts linked to existing stocks. We must now consider reducing these impacts and, at the same time, repairing environmental damage. This is an ambitious future research objective.

A possible nexus of minerals for the construction sector could be added to the one of metal-energy, by recovery of nickel slags. It could be globally positive if it fulfills several conditions. First, it should reduce the dependency of the island on imports of minerals that are indirectly responsible for one third of greenhouse gas emissions. A deeper analysis of imported minerals, and their use, should be conducted to estimate how recovered nickel slags could become a substitute for them. Second, nickel slag recovery should contribute to reducing the global contribution of the island to both

climate change and local pollution. The carbon footprint of various recovery possibilities should be assessed using Life Cycle Assessment, combined with Material Flow Analysis, to ensure the match between products obtained from nickel slag recovery, and local and closest foreign markets. Obviously, increasing transportation by exports of products recovered from nickel slags, possibly balanced by decreasing transportation of mineral imports, should be accounted for at the territorial level to assess the carbon footprint. Furthermore, the economic value of products issued from slag recovery is a crucial factor for the assessment. If there is no market for these products, there can be no hope of addressing imbalances in the island's metabolism. This global assessment is precisely the objective of the carboscories and carboval research projects studying the possibility of nickel slag recovery and using a mineralization process enabling CO₂ capture [78]. Third, local actors should be involved and take part in the strategic changes to come, in order to ensure that they can benefit from possible long-term evolution. Indeed, there is a strong risk of consolidating an economy based on the extraction of nonrenewable resources.

Finally, New Caledonia perfectly illustrates the metabolic challenges of small extractive islands. These small extractive islands have political economy issues in common because their metabolism reinforces their social, environmental, and economic vulnerabilities. As Anke Schaffartzik and Melanie Pichler point out [79], the role of extractive economies needs to be better understood by identifying synergies and trade-offs in the use of global resources. This is an issue of coupling approaches in political ecology and social ecology, in order to provide biophysical and socio-political conceptualizations within the interdisciplinary sustainability sciences. The “metal-energy-construction mineral” nexus has made it possible to grasp the complexity of the flow circulation and its environmental consequences. In this respect, this method makes it possible to enrich knowledge on the sustainable metabolic transformations of small extractive islands.

Author Contributions: Conceptualization, formal analysis; J.-B.B., P.H., A.V., N.A. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge funding from the “Agence calédonienne de l'énergie” (New Caledonian energy agency) and ADEME (French environmental agency), contract “Carboval” research project.

Acknowledgments: We want to thank the stakeholders that we interviewed and the reviewers for their valuable comments.

Conflicts of Interest: The authors declare no conflict of interest.

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