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DEVELOPMENT OF A FRAMEWORK AND A DECISION SUPPORT SYSTEM FOR THE SUTAINABLE EXPLOITATION OF RARE EARTH ELEMENTS

Author: Sotirios N. Kamenopoulos

Advising Committee:

Professor Konstantinos Komnitsas (supervisor)

Professor Zacharias Agioutantis, University of Kentucky, USA (co-supervisor)

Associate Professor Michael Galetakis (member)

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Sotiris Kamenopoulos

Examination Comittee:

Dr. Konstantinos Komnitsas, Professor, Technical University of Crete, Greece (supervisor)

Dr. Zacharias Agioutantis, Professor, University of Kentucky, College of Engineering, USA (co-supervisor)

Dr. Michael Galetakis, Associate Professor, Technical University of Crete, Greece (member of steering committee)

Dr. Anthimos Xenidis, Professor, National Technical University of Athens, School of Mining Engineering and Metallurgy, Greece

Dr. Iliana Halikia, Professor, National Technical University of Athens, School of Mining Engineering and Metallurgy, Greece

Dr. Konstantinos Tsakalakis, Professor, National Technical University of Athens, School of Mining Engineering and Metallurgy, Greece

Dr. Konstantinos Fytas, Professor, University of Laval, Canada

Glossary/Acronyms

DSS: Decision Support System

GRI: Global Reporting Initiative

IAEA: International Atomic Energy Agency

IISD: International Institute for Sustainable Development

MAUT: Multi-Attribute Utility Theory

MCDA: Multi-criteria Decision making

MMSD: Mining, Mineral and Sustainable Development

MMSS: Mining and Metals Sector Supplement

OECD: Organization for Economic Cooperation and Development

REEs: Rare Earth Elements

SMART: Simple Multi-Attribute Rating Technique

Sustainable Path: The path "that allows every future generation the option of being as well off as its predecessors" (USNRC)

USDoE: United States of America Department of Energy

USEIA: United States of America Energy Information Administration

USEPA: United States of America Environmental Protection Energy

USNAS: United States of America National Academy of Science

USNRC: United States of America National Research Council

USGS: United States of America Geology Survey

WSSD: World Summit on Sustainable Development

WTO: World Trade organization

Γλωσσάριο/Ακρωνύμια

ΜΚΟ: Μη Κυβερνητικές Οργανώσεις

ΣΓ: Σπάνιες Γαίες

ΣΥΑ: Σύστημα Υποστήριξης Αποφάσεων

Abstract

Global debates on mineral resources access, use and availability have gained a multi-dimension view the last years. The enormous economic and technological development of China, and other countries, leads to increased demand for critical raw materials such as Rare Earth Elements (REEs). The global production of REEs currently is monopolized by China. Both European Union and U.S. are almost 100% dependent on imports of REEs. The gap regarding exploration and process of REEs between Europe and U.S. from one side and China on the other side is growing, thus, turning China into a global dominant player. The relevant importance of REEs in terms of their uses, trade, the number of recent global initiatives, and the number of related geopolitical events/reports is doubtless. Consequently, mining of REE is an important challenge to the mining sector. Mining and production of REEs may be considered unique and different than other mining activities for two reasons: first, the presence of thorium and/or uranium in almost all REEs-bearing ores and, second, the complex metallurgy of REEs where there seems to be a lack of a standardized procedure for the extraction and refining of REEs. The concept of sustainable mining becomes even more complicated when applied to the mining of REEs since there are multiple paths for possible conflicts with stakeholders. Currently, there is a lack of a roadmap which may provide essential principles/best practices to sustainable mining of REEs. In addition, there is a lack of information regarding the assessment of REEs mining projects from the sustainability point of view. The best method to achieve the assessment of REEs mining projects is to use measurable qualitative and/or quantitative indicators. REEs mining projects are characterized by specific particularities as well as the potential presence of radiation. Thus, there is a need for a set of REEs-specific criteria and indicators to supplement Global Reporting Initiative (GRI)-based indicators. Moreover, the integration of Sustainable Development challenges and opportunities into the decision making process during the design and/or implementation of multi-disciplinary mining projects is generally not supported by Decision Support Systems (DSS).

The scope of this dissertation is the following: (a) to provide an insight and make efforts to highlight the multi-dimensional global importance of REEs, (b) to set the starting point and discuss potential important steps in a roadmap which may provide essential principles/best practices to sustainable mining of REEs, (c) to identify existing indicator sets and to lay out the importance of effective communication in both estimating a mine's contribution to sustainable development and gaining social license to operate, (d) to propose the adoption of

a framework that can be used to guide the extraction of Rare Earth Elements under Sustainable Development principles, and (e) to propose a new hybrid Decision Support tool which features an integrated assessment of Sustainable Development issues as they apply to mining projects. The proposed DSS framework named “ACROPOLIS DSS”, can be used to assist involved stakeholders in critical decisions, especially when addressing issues such as stakeholder participation, transparency, and trade-offs. The proposed DSS is based on Multi-Criteria Decision Analysis combined with Multi-Attribute Utility Theory.

This thesis investigates the development of a framework and a decision support system for the sustainable exploitation of rare earth elements. Results may be extrapolated also to metallic mines or aggregates quarries under the condition that the proposed Decision Support System will be properly modified in order to include relevant criteria and indicators.

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Εκτεταμένη Περίληψη

Στην παρούσα διατριβή πραγματοποιήθηκε η διερεύνηση της σχετικής σημασίας των σπάνιων γαιών (ΣΓ) σε σχέση με το εμπόριο, τον αριθμό των σχετικών πολιτικών και ερευνητικών πρωτοβουλιών που έχουν αναληφθεί τα τελευταία 6 έτη στις ΗΠΑ και στην ΕΕ, τον αριθμό των σχετικών γεωπολιτικών γεγονότων/αναφορών, και των προσπαθειών για το μετριασμό από την εξάρτηση από τις ΣΓ. Επίσης αναπτύχθηκε το διάγραμμα ροής (stream mapping) της παραγωγικής διαδικασίας για την εκμετάλλευση των ΣΓ, η αναγνώριση των εμπλεκομένων μερών (stakeholders) και η ανίχνευση των κινδύνων και των τρωτών σημείων της παραγωγικής διαδικασίας των ΣΓ. Στη συνέχεια προτείνεται το πλαίσιο για τη βιώσιμη εκμετάλλευση των ΣΓ και δημιουργήθηκε ένα καινοτόμο (state-of-the-art) Σύστημα Υποστήριξης Αποφάσεων-ΣΥΑ (Decision Support System-DSS) με την ονομασία «ACROPOLIS DSS» με τη χρήση του οποίου θα υποβοηθούνται οι αποφασίζοντες και τα εμπλεκόμενα μέρη (stakeholders) να αξιολογήσουν ένα έργο εκμετάλλευσης ΣΓ και να λαμβάνουν αποφάσεις του τύπου «GO-NO-GO» υπό την οπτική της Βιώσιμης Ανάπτυξης.

Το πλαίσιο για τη βιώσιμη εκμετάλλευση ΣΓ ενσωματώνει πέντε βασικούς «επικαλυπτόμενους» κύκλους (πυλώνες) Βιώσιμης Ανάπτυξης: την οικονομία, την κοινωνία, το περιβάλλον, την τεχνολογία και τη γεωπολιτική. Το προτεινόμενο πλαίσιο επίσης περιλαμβάνει τρεις ελεγκτικούς/περιοριστικούς παράγοντες: την πολιτική (policy), την κυβερνητική (governance) μαζί με τα εμπλεκόμενα μέρη, και διάφορους δείκτες οι οποίοι θα χρησιμοποιηθούν για τη λήψη αποφάσεων. Για την καλύτερη κατανόηση της έννοιας του «μονοπατιού βιώσιμης ανάπτυξης» υιοθετήθηκε ένα μοντέλο ανάλυσης ατυχημάτων («Swiss Cheese Model»). Οι πέντε επικαλυπτόμενοι κύκλοι (πυλώνες) Βιώσιμης Ανάπτυξης εξετάζονται από την κατακόρυφη τομή τους. Αυτή η νέα προσέγγιση προσδίδει μία πρακτική οπτική για την καλύτερη κατανόηση του «μονοπατιού βιώσιμης ανάπτυξης», την ποσοτικοποίηση της απόκλισης από το ιδανικό «μονοπάτι βιώσιμης ανάπτυξης», την παροχή δυνατότητας λήψης αποφάσεων στους αποφασίζοντες σε επίπεδο «go-no-go», και τη δυνατότητα αποφυγής συνθηκών που θα μπορούσαν να καταστήσουν το έργο μη-βιώσιμο. Επίσης αναγνωρίσθηκαν τα εξής:

- Η Κίνα είναι ο κυρίαρχος «παίκτης» στην παγκόσμια παραγωγή ΣΓ (σε ποσοστό μεταξύ 97%-99.8%).
- Οι ΗΠΑ, η ΕΕ και η Ιαπωνία είναι οι μεγαλύτεροι εισαγωγείς των Κινεζικών ΣΓ.

- Οι βασικές χρήσεις των ΣΓ περιλαμβάνουν την ενέργεια και την αμυντική βιομηχανία.
- Η εφαρμογή των ΣΓ οδηγεί σε χαμηλά κόστη και ενεργειακή αποδοτικότητα.
- Μεγάλος αριθμός πρωτοβουλιών από τις ΗΠΑ και την ΕΕ σχετικών με τις ΣΓ έχει αναληφθεί από το 2010.
- Η υποκατάσταση των ΣΓ σήμερα είναι σπάνια, ή/και αδύνατη, ή/και σε εμβρυακό στάδιο.
- Η δυνατότητα ανακύκλωσης των ΣΓ εμποδίζεται από ένα αριθμό τεχνικών περιορισμών.
- Ένας σημαντικός αριθμός σημαντικών γεωπολιτικών γεγονότων σχετικών με τις ΣΓ συνέβησαν από το έτος 2010.
- Το διάγραμμα ροής της παραγωγικής διαδικασίας των ΣΓ περιλαμβάνει την εξόρυξη του μεταλλεύματος, τη θραύση, την λειοτρίβηση, την επίπλευση, τη χημική επεξεργασία, τον εξευγενισμό, και την διαμόρφωσή τους σε κατάλληλη μορφή αναλόγως της χρήσης του τελικού προϊόντος.
- Τα βασικά εμπλεκόμενα μέρη (stakeholders) στην παραγωγή των ΣΓ είναι οι εξορυκτικές επιχειρήσεις, οι εργαζόμενοι, η κοινωνία, οι πολιτικοί, οι Τοπικές/Περιφερειακές/Εθνικές αρχές, οι Μη Κυβερνητικές Οργανώσεις, και τα Μέσα Μαζικής Ενημέρωσης.
- Από την πλευρά του περιβάλλοντος, οι διαδικασίες εξόρυξης ΣΓ αναμένεται να είναι παρόμοιες με κάθε άλλη διαδικασία εξόρυξης άλλων μετάλλων. Εκτός από την πιθανή παρουσία ραδιενέργειας (εξαιτίας της πιθανής παρουσίας ουράνιου ή/και θόριου), οι δυνητικές εκπομπές αποβλήτων/ρύπων είναι ανάλογες με αυτές της εξόρυξης ενός τυπικού μεταλλεύματος.
- Τα Μέσα Μαζικής Ενημέρωσης παίζουν σημαντικό ρόλο ως εμπλεκόμενα μέρη (stakeholders) στην παραγωγή ΣΓ. Ο ρόλος των Μέσων Μαζικής Ενημέρωσης μπορεί να είναι είτε θετικός, είτε αρνητικός.
- Οι σημαντικότεροι παράγοντες οι οποίοι επηρεάζουν την αγορά των ΣΓ είναι η κυριαρχία της Κίνας στην παραγωγή των ΣΓ, το μείγμα της προσφοράς/ζήτησης/τιμών των ΣΓ, οι εξαγωγικές περιοριστικές πολιτικές της Κίνας, το λαθρεμπόριο, οι μη-ορθές πολιτικές πρακτικές, η απροθυμία της Κίνας να εφαρμόσει περιβαλλοντικούς και εργασιακούς κανονισμούς, η ύπαρξη αυστηρών περιβαλλοντικών και εργασιακών κανονισμών/νόμων στις δυτικές χώρες, οι οικονομικές και αναπτυξιακές παγκόσμιες επικρατούσες συνθήκες, το γεγονός πως οι

ΣΓ δεν αποτελούν αντικείμενο εμπορικής διαπραγμάτευσης/συναλλαγής σε Αγορές ή Ανταλλαγές Μετάλλων, διάφορα γεωπολιτικά θέματα, η έλλειψη υποκατάστατων των ΣΓ και το γεγονός πως η ανακύκλωση των ΣΓ προσκρούει σε ένα αριθμό περιορισμών.

- Διάφοροι κίνδυνοι υπάρχουν κατά τη διάρκεια παραγωγής των ΣΓ, όπως η πιθανή παρουσία ραδιενέργειας, οι εκπομπές CO_2, η παρουσία βαρέων μετάλλων και η χρήση οξέων, η πιθανή εμφάνιση φθοριούχων ενώσεων, η πιθανή έκλυση σκόνης, και άλλοι λοιποί κίνδυνοι σχετικοί με την υγιεινή και ασφάλεια της εργασίας.
- Οι επιπτώσεις αυτών των κινδύνων αναμένεται να επηρεάζει πιθανώς όλα τα εμπλεκόμενα μέρη (stakeholders).

Όπως προαναφέρθηκε, η παρούσα διατριβή προτείνει ένα πλαίσιο για την αξιολόγηση της συμμόρφωσης έργων εκμετάλλευσης ΣΓ με τις αρχές της Βιώσιμης Ανάπτυξης. Η δυνατότητα μίας εξορυκτικής επιχείρησης για να αποκτήσει την «Κοινωνική Άδεια Λειτουργίας» (Social License to Operate) και να ακολουθεί τις αρχές της Βιώσιμης Ανάπτυξης, εξαρτάται από την παρουσία σταθερής οικονομίας, ισορροπημένων κοινωνικών προσδοκιών πχ. δίκαιης κατανομής παραγόμενου πλούτου και κινδύνου, και ύπαρξη εμπιστοσύνης. Συνήθως η εμπιστοσύνη υπονομεύεται από την έλλειψη διαφάνειας. Αντιστρόφως, όταν ακολουθείται ένα μονοπάτι καθαρής επικοινωνίας χρησιμοποιώντας κριτήρια και δείκτες Βιώσιμης Ανάπτυξης σε συνδυασμό με ορθές πρακτικές Βιώσιμης Ανάπτυξης, διευκολύνεται η δημιουργία εμπιστοσύνης και απόκτησης της «Κοινωνικής Άδειας Λειτουργίας». Η ειλικρινής ανταλλαγή απόψεων μεταξύ των εμπλεκομένων μερών (εξορυκτική επιχείρηση, κυβέρνηση και τοπική κοινωνία), και η σαφήνεια των μηνυμάτων αποτελεί ένα προσύμφωνο μεταξύ των εμπλεκομένων μερών το οποίο στηρίζεται πάνω σε χειροπιαστά κριτήρια και ποσοτικοποιημένους δείκτες.

Από τα τέλη της δεκαετίας του 1990 καταβλήθηκαν αρκετές προσπάθειες για τη δημιουργία κριτηρίων και δεικτών Βιώσιμης Ανάπτυξης στον εξορυκτικό τομέα. Οι μεγάλες εξορυκτικές επιχειρήσεις χρησιμοποιούν κυρίως τους δείκτες «Global Reporting Initiative-GRI)» και τους δείκτες «Mining and Metals Sector Supplement-MMSS». Το συγκεκριμένο πλαίσιο περιέχει μεν σημαντική πληροφορία, με συγκεντρωτικά χαρακτηριστικά για ολόκληρη την παραγωγική διαδικασία μίας εξορυκτικής επιχείρησης, αλλά, δεν περιλαμβάνει δεδομένα τα οποία άμεσα να σχετίζονται με τις ιδιαιτερότητες της εκμετάλλευσης των ΣΓ. Η εκμετάλλευση των ΣΓ χαρακτηρίζεται από ιδιαίτερα τεχνικά, οικονομικά και γεωπολιτικά χαρακτηριστικά. Κοιτάζοντας αρχικώς τα τεχνικά θέματα, τα κοιτάσματα ΣΓ περιέχουν θόριο ή ουράνιο τα οποία απαιτούν διαχείριση με ασφαλή τρόπο. Υπάρχουν διάφοροι τύποι κοιτασμάτων, κάθε ένα από τα οποία απαιτούν ιδιαίτερο χειρισμό με συγκεκριμένο και κατάλληλο τρόπο. Ως εκ τούτου, σε αντίθεση πχ. με την εκμετάλλευση/εξόρυξη του γαιάνθρακα ή του χαλκού, δεν υπάρχουν γενικά εφαρμοστέα πρότυπα για την εκμετάλλευση ΣΓ.

Οι ανησυχίες για το πώς θα διαχειρισθεί η ραδιενεργός ακτινοβολία και οι τυχόν περιβαλλοντικές επιπτώσεις οδήγησαν σε αντίσταση/αντίθεση εναντίον έργων εκμετάλλευσης ΣΓ σε ορισμένες τοπικές κοινωνίες. Οι ανησυχίες και οι φόβοι του δημόσιου κοινού και των τοπικών κοινωνιών δεν είναι αδικαιολόγητοι. Στο παρελθόν έχουν υπάρξει περιπτώσεις ορυχείων ΣΓ, όχι απαραίτητα στην Κίνα, οι οποίες έχουν ρυπάνει το περιβάλλον. Πέντε ακόμη ιδιαιτερότητες των ΣΓ αναγνωρίσθηκαν: η σημασία της αγοράς, το λαθρεμπόριο, οι παράνομες εξορύξεις, η ιδιαίτερη προσοχή που προσδίδουν τα Μέσα Μαζικής Ενημέρωσης, και η κυριαρχία της Κίνας. Καθένα από αυτά έχει τη δυνατότητα να επηρεάσει οποιονδήποτε ή όλους από τους πέντε πυλώνες της Βιώσιμης Ανάπτυξης: περιβάλλον, οικονομία, κοινωνία, τεχνολογία και γεωπολιτική. Όταν εκλαμβάνονται ως σύνολο, αυτές οι ιδιαιτερότητες δημιουργούν μια πρόκληση για όσες εξορυκτικές επιχειρήσεις προσπαθήσουν να αναπτύξουν νέα ορυχεία ΣΓ. Για την υποβοήθηση στην επικοινωνία μεταξύ των εμπλεκομένων μερών επιλέχθηκαν να χρησιμοποιηθούν συγκεκριμένα κριτήρια και δείκτες, σε συνδυασμό με δείκτες προτεινόμενους από την πρωτοβουλία GRI.

Τα επιλεγμένα κριτήρια και δείκτες καλύπτουν όλο το φάσμα των πέντε πυλώνων Βιώσιμης Ανάπτυξης (περιβάλλον, οικονομία, κοινωνία, τεχνολογία, γεωπολιτική). Τα ζεύγη κριτηρίων/δεικτών που δημιουργήθηκαν αντιμετωπίζουν τις ιδιαιτερότητες των έργων εκμετάλλευσης ΣΓ, και δεδομένου του ξεκάθαρου τρόπου επικοινωνίας που δημιουργούν μεταξύ των εμπλεκομένων μερών, μπορούν από τη μία πλευρά, μελλοντικά να βοηθήσουν τους αποφασίζοντες να λάβουν αποφάσεις για έργα εκμετάλλευσης ΣΓ, και από την άλλη, να επηρεάσουν την ικανότητα του έργου εκμετάλλευσης να διατηρήσει την «Κοινωνική Άδεια Λειτουργίας». Επιπλέον, το νέο σύνολο κριτηρίων και δεικτών θα πρέπει να θεωρηθεί ως ένα βασικό εργαλείο, το οποίο μπορεί να ενισχυθεί, τροποποιηθεί ή/και να προσαρμοσθεί ανάλογα με τις ανάγκες/ιδιαιτερότητες του κάθε έργου εκμετάλλευσης ΣΓ. Γενικότερα, οι επιλεγμένοι δείκτες και τα κριτήρια, θα μπορέσουν να υποστηρίξουν την ανάλυση/κατανόηση ενός έργου εκμετάλλευσης ΣΓ και τη συνεισφορά του έργου στη Βιώσιμη Ανάπτυξη, συμπεριλαμβανομένου του τρόπου με τον οποίο ένα ορυχείο συμβάλει στην επίτευξη των στόχων για την παγκόσμια Βιώσιμη Ανάπτυξη (Sustainable Development Goals-SDG) που έχει θέσει ο Οργανισμός Ηνωμένων Εθνών για κάθε συγκεκριμένη περιοχή. Αυτό θα καταστεί επωφελές γιατί ο τομέας των εξορύξεων έχει τη δυνατότητα να είναι ο καταλύτης και ο οδηγός για την παγκόσμια βιώσιμη οικονομική ανάπτυξη, καθώς οι επικρατούσες πρακτικές δεν μπορούσαν μέχρις στιγμής να λάβουν υπόψη τις ιδιαιτερότητες των έργων εκμετάλλευσης ΣΓ.

Επιπλέον, αν μία εξορυκτική επιχείρηση μπορεί να αποδείξει μέσω στοιχειοθετημένων αναφορών ότι ένα ορυχείο ΣΓ μπορεί να συμβάλλει θετικά στην κοινωνία, είναι πολύ πιο πιθανό να αποκτήσει την «Κοινωνική Άδεια Λειτουργίας». Η προσέγγιση που έχει αναπτυχθεί στην παρούσα διατριβή θα μπορούσε να προσαρμοσθεί σε άλλες συνθήκες εξόρυξης ορυκτών όπου υπάρχουν μοναδικά προβλήματα. Για παράδειγμα, υπάρχει σημαντικό ενδιαφέρον για τις υποθαλάσσιες εξορύξεις ορυκτών. Οι προαναφερθέντες πρωτοβουλίες/πρωτόκολλα GRI και MMSS δεν καταγράφουν όλη την πληροφορία που απαιτείται να συλλεχθεί και να διαμοιρασθεί μεταξύ των πιθανών εμπλεκομένων μερών για τέτοιου είδους έργα. Επιπλέον υπάρχουν και τρεις περιορισμοί. Καταρχήν, οι Στόχοι του ΟΗΕ για την παγκόσμια Βιώσιμη Ανάπτυξη (SDGs), τουλάχιστον όσο διαρκούσε η εκπόνηση της παρούσας διατριβής, βρισκόταν ακόμη υπό ανάπτυξη οπότε πιθανώς να χρειασθεί η αναπροσαρμογή των κριτηρίων και των δεικτών. Δεύτερον, για την καταγραφή ων κριτηρίων και των δεικτών απαιτείται συλλογή αρκετών δεδομένων, πράγμα το οποίο είναι δαπανηρό και αρκετές εξορυκτικές επιχειρήσεις ίσως υψώσουν εμπόδια σε αυτό. Τέλος, δεν είναι σαφές αν οι κρατικές ελεγχόμενες επιχειρήσεις εξόρυξης σε ορισμένα μέρη του κόσμου θα έχουν τα κίνητρα ώστε να δεσμευθούν για την παροχή εκτεταμένων αναφορών, δεδομένου του γεγονότος ότι οι κρατικές επιχειρήσεις δεν χρειάζονται ίσως «Κοινωνική Άδεια Λειτουργίας», σε αντίθεση με τις ιδιωτικές εξορυκτικές επιχειρήσεις.

Η Ατζέντα για την παγκόσμια Βιώσιμη Ανάπτυξη μέχρι το έτος 2030 που έθεσε ο Οργανισμός Ηνωμένων Εθνών απαιτεί την εκπλήρωση 17 Στόχων Βιώσιμης Ανάπτυξης οι οποίοι με τη σειρά τους απαιτούν δημιουργικότητα και καινοτομία για την αντιμετώπιση των προκλήσεων. Μέχρις στιγμής, έχουν αναπτυχθεί μια σειρά από μοντέλα Συστημάτων Υποστήριξης Αποφάσεων (ΣΥΑ) σε διαφορετικά πεδία της Βιώσιμης Ανάπτυξης χρησιμοποιώντας διάφορες μεθοδολογίες και τεχνικές. Στην παρούσα διατριβή προτείνεται ένα καινοτόμο (state-of-the-art) Σύστημα Υποστήριξης Αποφάσεων με την ονομασία «ACROPOLIS DSS» με τη χρήση του οποίου θα υποβοηθούνται οι αποφασίζοντες και τα εμπλεκόμενα μέρη (stakeholders) να αξιολογήσουν ένα έργο εκμετάλλευσης ΣΓ και να λαμβάνουν αποφάσεις του τύπου «GO-NO-GO» υπό την οπτική της Βιώσιμης Ανάπτυξης. Η παρούσα διατριβή ενσωματώνει το καινοτόμο ΣΥΑ εντός ενός προτεινόμενου Πλαισίου Βιώσιμης Ανάπτυξης για τις ΣΓ. Το καινοτόμο ΣΥΑ βασίζεται στην Πολυκριτήρια Ανάλυση Αποφάσεων (Multi-criteria Decision Analysis-MCDA) και στη Θεωρία Χρησιμότητας Πολλαπλών Ιδιοτήτων (Multi-attribute Utility Theory-MAUT). Το προτεινόμενο καινοτόμο ΣΥΑ παρέχει τη δυνατότητα προσέγγισης των εννοιών της Βιώσιμης Ανάπτυξης «*συμμετοχή των πολιτών*» και «*διαφάνεια*» στη διαδικασία λήψης αποφάσεων, όπως περιγράφεται και συνίσταται σε προηγούμενα έτη από τα Ηνωμένα Έθνη, με ολιστικό και ποσοτικοποιημένο τρόπο. Επιπλέον, το προτεινόμενο ΣΥΑ παρέχει τη δυνατότητα να εντοπισθεί, να ποσοτικοποιηθεί και να μετρηθεί η έννοια του «Βιώσιμου Μονοπατιού», όπως ορίζεται από το Εθνικό Συμβούλιο Έρευνας των ΗΠΑ (US National Research Council-NRC). Η καινοτομία του προτεινόμενου ΣΥΑ είναι εμφανής όταν ληφθούν υπόψη τα ακόλουθα:

- Παρέχει στα εμπλεκόμενα μέρη την ευκαιρία για διαφανή, ελεύθερη λήψη αποφάσεων με ανοικτές διαπραγματεύσεις μέσα στα διάφορα στάδια της υπολογισμού των βαρών των κριτηρίων και των δεικτών και διαμέσου πολυάριθμων επιπέδων συμβιβασμών, όπως αυτό απαιτείται από τον ορισμό της Βιώσιμης Ανάπτυξης. Αυτές οι συνθήκες μπορούν να αυξήσουν την πιθανότητα των εταιρειών να αποκτήσουν και να διατηρήσουν την «Κοινωνική Άδεια Λειτουργίας».
- Το προτεινόμενο καινοτόμο ΣΥΑ είναι σχεδιασμένο να συνδυάζει σωστά ποσοτικούς δείκτες πριν από την εφαρμογή ενός έργου εκμετάλλευσης ΣΓ και θέτει τη βάση για την αξιολόγηση του έργου υπό την οπτική της Βιώσιμης Ανάπτυξης πριν την έναρξη του έργου, κατά τη διάρκεια του έργου, και μετά την υλοποίηση του έργου εξόρυξης (μετά την λήξη).

Το προτεινόμενο καινοτόμο ΣΥΑ βρίσκεται ακόμη σε μορφή πρωτοτύπου, προφανώς επιδέχεται περαιτέρω βελτιώσεων, αλλά θέτει τη βάση για το τι πρέπει να λαμβάνεται υπόψη όταν διάφορα έργα εκμετάλλευσης ΣΓ καθυστερούν λόγω του αριθμού των συγκρούσεων μεταξύ των εμπλεκομένων μερών. Είναι σαφές ότι η περαιτέρω έρευνα κρίνεται απαραίτητη για την επίτευξη του στόχου της δημιουργίας ενός κοινά αποδεκτού ΣΥΑ για το σχεδιασμό και την υλοποίηση των έργων εκμετάλλευσης ΣΓ σύμφωνα με τις αρχές της Βιώσιμης Ανάπτυξης. Η παρούσα διατριβή αφορά αποκλειστικά και μόνο τη δημιουργία ενός πλαισίου και συστήματος υποστήριξης αποφάσεων για τη βιώσιμη αξιοποίηση των σπάνιων γαιών. Ωστόσο, η εφαρμογή του προτεινόμενου ΣΥΑ θα μπορούσε να επεκταθεί και στην περίπτωση άλλων εκμεταλλεύσεων (πχ. μεταλλευμάτων, αδρανών κλπ.) με την προϋπόθεση ότι θα τροποποιηθεί αναλόγως με την προσθήκη/αφαίρεση ορισμένων δεικτών/κριτηρίων/εμπλεκομένων μερών ώστε να είναι κατάλληλο για κάθε περίπτωση.

Ο συγγραφέας της παρούσας διατριβής εφόσον καταστεί δυνατό θα προσπαθήσει να συνεχίσει τη βελτίωση του προτεινόμενου ΣΥΑ και να ελέγξει περαιτέρω την αξιοπιστία του χρησιμοποιώντας πραγματικά δεδομένα από έργα εκμετάλλευσης ΣΓ.

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6. Kamenopoulos, S., Agioutantis, Z., Komnitsas, K., 2015b. A Framework for Sustainable Mining of Rare Earth Elements. Rare Earths Industry: Technological, Economic, and Environmental Implications, Chapter 7. Eds.: Ismar Borges De Lima and Walter Leal Filho, Elsevier Publications, ISBN: 978-0-12-802328-0.

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Chapter 1. Introduction - Motivation for this Research

Global debates on mineral resources access, use and availability have gained a multi-dimension view the last years. The enormous economic and technological development of China, and other countries, leads to increased demand for critical raw materials such as Rare Earth Elements (REEs). The role of REEs is crucial to clean energy efficiency economy. The main end uses of REEs include the energy and defense sectors. Applications of REEs may provide low cost and energy efficiency. The global production of REEs currently is monopolized by China. Both the European Union and the U.S. are almost 100% dependent on imports of REEs. The academic gap between Europe and U.S. from one side and China on the other side is growing, thus, turning China into a global dominant player. Mining and production of REEs may be considered unique and different than other mining activities for two reasons: first, the presence of thorium and/or uranium in almost all REEs-bearing ores and, second, the complex metallurgy of REEs, which is the result of low grade ores, and which is responsible for the lack of a standardized procedure for the extraction and refining of REEs. The concept of sustainable mining becomes even more complicated when applied to the mining of REEs.

1.1 Innovation

Currently, there is a complete lack of information regarding evaluating REEs mining projects from the sustainability point of view. In addition there is a lack of a roadmap which may provide essential principles and/or best practices to sustainable mining of REEs. Furthermore, mining of REEs is characterized by two basic attributes. The first attribute is the presence of thorium and/or uranium in many REE-bearing ores. This attribute is directly associated to unwanted radioactivity. The second attribute originates by the term “elements” itself: a reference to REEs is actually a reference to 17 different elements, so, it is uncommon to find identical REEs ores and therefore the extraction and refining of REEs depends on different procedures. In addition to these attributes, the sustainable development of REEs mining projects is faced with specific particularities. These particularities differentiate the way that REEs mining projects should be treated from the sustainability point of view. As a result decision makers that are involved in REEs projects do not have a complete picture of the decision making framework. The aim of this thesis is for the first time to fill this gap and develop a subject decision making framework.

1.2 Dissertation Structure

This dissertation is structured as follows:

The second chapter provides a historical review and the background. It describes the multidimensional global importance of Rare Earth Elements (REEs), the end uses of REEs and examples for cost and energy efficiency implications of REEs. In addition it describes the major characteristics that differentiate REEs from other minerals. The relevant importance of REEs in terms of trade, the number of initiatives related to REEs undertaken in US/EU, the number of geopolitical events/reports related to REEs, and the level of REEs mitigation of supply risk was also investigated in the second chapter.

The third chapter presents the stream mapping of the REEs production process.

The fourth chapter identifies the stakeholders of REEs mining projects (i.e. the environment, the public, the employees, the media, the markets, the governments/NGOs and the mining companies). This chapter also discusses some of the most worth mentioned “effects” of each stakeholder.

The fifth chapter describes the hazards / vulnerabilities of each production process of REEs as well as the affected stakeholders based on the Stream Mapping Process which was presented in the third chapter.

The sixth chapter focuses on issues of Sustainable Development. It provides some historical background, the definition and the schematic models of Sustainable Development. Subsequently, this chapter describes the proposed framework, and its application, for the sustainable exploitation of REEs.

The seventh chapter focuses in the evaluation of REEs mining projects from the sustainability point of view. It presents a set of supplementary sustainable development criteria and indicators (C&I), developed specifically for REEs mining projects, incorporating the unique particularities that differentiate REEs projects from other mineral mining projects. This chapter also analyses the relation between the stakeholders’ communication and the Social License to Operate.

The eighth chapter describes the hybrid Decision Support System for evaluating the sustainability of REEs mining projects. The proposed tool is based on an integrated indicators-based SD assessment process for supporting decision making in REEs mining projects. The background section of this chapter reviews and discusses different DSSs that have been proposed in a Sustainable Development context as applied to different sectors. Then the methodology used for the creation of subject DSS is followed. The proposed DSS is based on Multi-Criteria Decision Analysis (MCDA) combined with Multi-Attribute Utility Theory (MAUT).

The final, ninth chapter, summarizes the work done in this dissertation. It describes the evolution attained in the scientific direction and provides conclusions with suggestions for further research.

Chapter 2. Historical Review - Background

The Rare Earth Elements (REEs) are 17 elements with atomic numbers 57 through 71 on the periodic table; they include the fifteen lanthanides, as well as scandium and yttrium. These are: Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), Lutetium (Lu), Yttrium (Y) and Scandium (Sc). They are divided into two categories depending on atomic weight: the light REEs are lanthanum through europium (atomic numbers from 57 through 63) and the heavy REEs are gadolinium through lutetium (atomic numbers from 64 through 71). Yttrium, with atomic number 39 is considered as heavy REEs due to its chemical and physical association with the heavy REEs, (Long et al. 2010). The global reserves of REEs are estimated at 130 million tones (USGSa, 2016). The world total production it is estimated at 124,000 tones, (USGSa, 2016). This amount is considered low compared to the estimated REEs global reserves (0.1% of estimated global reserves). China produces approximately 97% (130,000 tones) of REEs. In some cases, China controls up to 99.8% of world REEs production. These are the cases of dysprosium, yttrium, terbium, europium and neodymium, (USDOE, 2010). For these reasons, currently China is considering a dominant player in REEs world production. Recent estimates of REEs reserves by country are shown in Figure 1 (statista.com, 2016). Regarding European REEs deposits there is limited information and no extensive explorations are known, (Oko-Institute, 2011). Most of Chinese deposits of REEs are found in the region of Bayan Obo (Inner Mongolia). In the US, the biggest ore deposit is located in Mountain Pass, California. The mine in Mountain Pass started operations in 1952 and closed in 2002. As a result, currently there is no mining of REEs in the US. Mountain Pass was the biggest mine of REEs in US. The facility is currently undergoing expansion and modernization, and expected to be back up soon to full production. In September 2011, the USGS announced an estimation of at least 1 million metric tons of REEs resources within the Khanneshin carbonatite in the Helmand Province, Afghanistan, (USGS, 2011a).

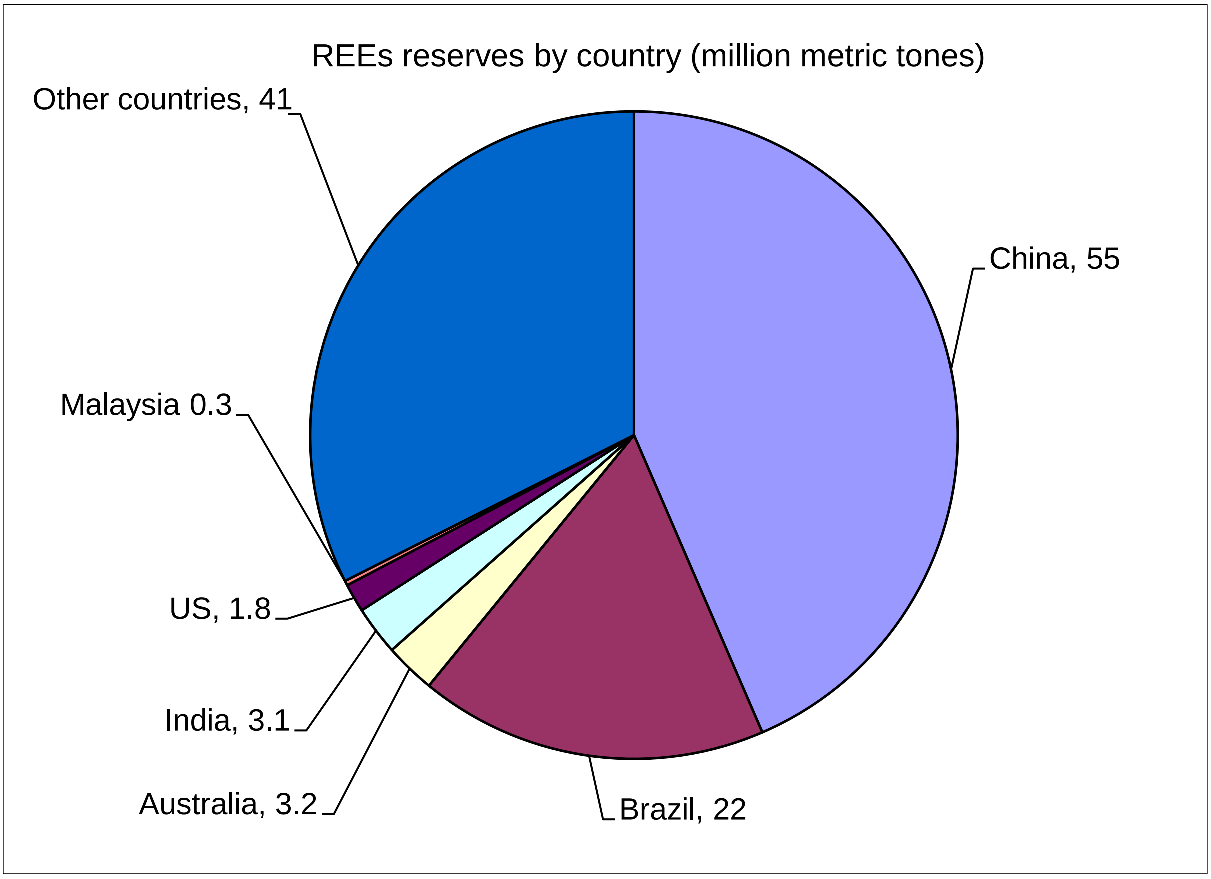

Figure 1 Global REEs reserves by country (source: https://www.statista.com/statistics/277268/rare-earth-reserves-by-country/, 2016)

2.1 End Uses and Examples for Cost and Energy Efficiency Implications of REEs

This section describes the basic uses of REEs in the components of several products, (USDOE, 2010; Oko-Institute, 2011; Hurst, 2010a; Humphries, 2010; Grasso, 2011; USGS, 2002; Becker, 2010; USGS, 2011b; Hurst, 2010b) and also gives some examples of the cost and energy efficiency implications of REEs. Table 1 shows the main uses of each element. The information regarding use of REEs in defense industry is limited. It is reported that they are used in the following defense sectors: guidance and control systems, electronic war, targeting and weapon systems, electric motors, and communication, (Grasso, 2011). REEs may also be used as components of alloys of other metals. In that case, they increase or decrease ductility and softness, they can increase metals anti-rusting properties, and make the metal resistant to creep e.g., turbine blades of a jet engine (Becker, 2010).

2.1.1 Light Bulbs

The U.S. Energy Information Administration (USEIA) estimates that in 2015, about 404 billion kilowatt-hours (kWh) of electricity were used for lighting by the residential sector and the commercial sector in the United States. This was about 15% of the total electricity consumed by both of these sectors and about 10% of total U.S. electricity consumption. Residential lighting consumption was about 145 billion kWh or about 10% of total residential electricity consumption in 2015 (USEIA, 2016a).

The average Residential Retail Price of Electricity in the US for 2015 was 12.65 cents per kWh (USEIA, 2016b); thus the total cost for 2015 US residential lighting consumption was approximately $18.34 billion. Compact fluorescent light bulbs, which contain europium, terbium and yttrium, use up to 75% less energy than traditional incandescent light bulbs. As a result the 75% decrease in US residential lighting consumption would lead to savings of approximately $13.75 billion per year. Yet, it should be noted that the above ascertainment may not be proved since it does not take into consideration a large number of fluorescence and/or LED luminaires. As it was mentioned above, the remainder 259 billion kWh was consumed for lighting by the commercial sector (USEIA, 2016a). The average Commercial Retail Price of Electricity in the US for 2015 was 10.64 cents per kWh; thus the total cost for 2015 US commercial lighting consumption was approximately $27.55 billion. The 75% decrease in US commercial lighting consumption would lead to additional savings of approximately $20.6 billion.

2.1.2 Electrically-driven Vehicles

A large percentage of global electrical energy is consumed by driven motors (i.e. refrigerators, air conditioners, washing machines, elevators/escalators, laptops, computers etc.). The most efficient motors require the rare earths neodymium and praseodymium coupled with small amounts of dysprosium and terbium. The advantages of these motors are longer life spans, little maintenance, smaller sizes and higher efficiency. It has been estimated that efficiency of a REEs-based motor is 10 to 20% higher than that of an induction motor, (Hitachi Metals Co., 2014).

2.1.3 Automotive

One luxury vehicle may contain more than 100 motors inside. Cost and reliability are key factors for automotive motors. A REEs-based motor is generally used in hybrid-electrical vehicles as in compressor motors in air conditioners, electric power steering, in gear shift etc. The efficiency of a REEs-based motor is 10 to 20% higher than that of an induction motor. In that case, it has been estimated that the CO_2 savings is approximately up to 3.5%, (Hitachi, 1994; Hitachi Metals Co., 2014).

Table 1 Main End Uses of REEs (USDOE, 2010)

Material	Energy Uses	Other Uses
Lanthanum	• As a catalyst for vehicles and aircraft fuels • In NiMH batteries either as high purity material or part of mixed metals (a combination of Ce, La, Nd and Pr)	• In glass crystal structure for optical lens • In night vision instruments • In carbon arc lamps, color television sets, cigarette lighter flints, and optical fibers • In X-ray films and certain lasers
Cerium	• For catalytic converters in automobiles and petroleum industry • In nickel metal hydride (NiMH) batteries (hybrid and electric vehicles) • In phosphor powders in linear fluorescent fluorescent light bulbs	• As an oxide in glass polishing agents • In carbon-arc lighting, especially in the motion picture industry • In manufacturing of pyrophoric alloys for cigarette lighters
Praseodymium	• In neodymium-iron-boron magnets (NdFeB) (electric vehicle motors and wind turbine generators) • In mixed metals for nickel metal hydride batteries.	• As an alloying agent with magnesium to create high-strength metals used in aircraft engines • In the motion picture industry (forming forms the core of carbon arc lighting) • In optic cables as a doping agent it is used as a signal amplifier
Neodymium	• In NdFeB permanent magnets (electric vehicle motors and wind turbine generators)	• In CRT glasses to enhance picture brightness by absorbing yellow light wavelengths. • In laser and medicine technology
Samarium	• Permanent magnets	
Europium	• In producing white light of helical fluorescent light bulbs • A primary component in the production of fluorescent tubes	• In laser technology • As an oxide in television sets
Gadolinium	• In phosphors industry for color televisions	• In magneto-optic recording technology • In Magnetic Resonance Imaging (MRI)
Terbium	• In fuel cells that operate at high temperatures. • In energy efficient fluorescent lamps	
Dysprosium	• In NdFeB permanent magnets (electric vehicle motors and wind turbine generators)	
Holmium	CURRENTLY NO USES. It possesses unusual magnetic properties that could be exploited in the future.	
Erbium	• As an amplifier for fiber optic data transmission • In lasers for medical and dental uses	
Thulium		• In sensitive X-ray phosphors
Ytterbium		• In stress gauges to monitor ground deformations

Material	Energy Uses	Other Uses
Lutetium	• As catalyst in cracking, alkylation, hydrogenation, and polymerization	• In detectors in positron emission tomography (PET).
Yttrium	• In television tubes to provide the red coloring	• In microwave communication devices for the defense and satellite industries • In frequency meters, magnetic field measurement devices, tunable transistors • As stabilizers for exotic light-weight jet engine turbines and other parts and as a stabilizer material in rocket/missiles nose cones • In laser crystals specific to spectral characteristics for military communications
Scandium		• In lasers and consumer electronics

2.2 What Differentiates REEs from Other Minerals

The two major characteristics that differentiate REEs from other minerals are related to their chemical and magnetic behavior. The chemical, metallurgical, and physical behaviors of the rare earths are governed by the electron configuration of these elements. In general, these elements are trivalent; R^{3+}, but several of them have other valences. The number of 4*f* electrons of each lanthanide is given in the table of the number of 4*f* electrons and ionic radii for the R^{3+} ion. The 4*f* electrons have lower energies than and radially lie inside the outer three valence electrons (i.e., 4*f* electrons are "localized" and part of the ion core), and thus they do not directly participate in the bonding with other elements when a compound is formed. This is why the lanthanides are chemically similar and difficult to separate and why they occur together in various minerals. The outer or valence electrons for the 14 lanthanides and lanthanum are the same, $5d6s^2$; for scandium, $3d4s^2$; and for yttrium, $4d5s^2$. There is some variation in the chemical properties of the lanthanides because of the lanthanide contraction and the hybridization, or mixing, of the 4*f* electrons with the valence electrons (Encyclopedia Britannica, 2014).

The magnetic moments of the rare–earth metals are dominated by the spin contribution from the highly localized 4*f* electrons, and are thus good examples of local–moment ferromagnets. As the 4*f* electron shell can accommodate 14 electrons, a half–filled shell has seven electrons with parallel spins (according to Hunds' rule, the empirical rule in atomic physics that states that in general parallel spins are a lower–energy configuration than anti-parallel spins). Thus, the 4f electrons contribute 7 μB to the total magnetic moment of Gd (~ 7.6 μB), and similarly large contributions to the total moments for the other magnetic rare–earth metals. In contrast to the situation with itinerant ferromagnets (based on the magnetic transition metals), the valence electrons contribute a small fraction of the overall magnetic moment per atom — in the case of Gd, the 5d 6s valence electrons contribute 0.6 μB, less than 10% of the total moment. The magnetic structures of the rare–earth metals and many rare–earth–based compounds are well understood as the result of many decades of experimental study and the development of the local spin–density approximation in calculations of the valence electronic structures of solids (Barett and Dhesi, 2001).

2.3. Relevant Importance of REEs

The relevant importance of REEs in terms of trade, the number of initiatives related to REEs undertaken in US/EU, the number of geopolitical events/reports related to REEs, and the level of REEs mitigation of supply risk was investigated as shown below.

2.3.1 Trade

The major importers of REEs in 2008 were Europe, US and Japan. The amounts of imported REEs are given in Table 2, (Oko-Institute, 2011).

Table 2 Major Importers of REEs (Oko-Institute, 2011)

	Imports (t)	Share of imports from China (%)
EU 27	23,013	90
USA	20,663	91
JAPAN	34,330	91

Figure 2 shows the share of European countries in terms of the total imports of REEs from outside EU-27 for the year 2008, (Oko-Institute, 2011). The first worldwide commercial production of a REEs-based product ("*REEs-based flints*") occurred in 1903 at Treibach in Austria, (Avalon Rare Metals, 2009). In Europe there are only a few industrial activities involving rare earth refining and processing. In Figure 2 we may see that Austria has a potential REEs import share (24%). The reason for that could be that one of the biggest European industries specialized in manufacturing processes for semi-finished or finished products which contain REEs, such as magnets, alloys, automotive catalysts, etc., is based in Austria (Treibacher Industrie AG) (EC, 2012) and (Treibacher Industrie AG, 2014). Treibacher Industrie AG was founded in 1898.

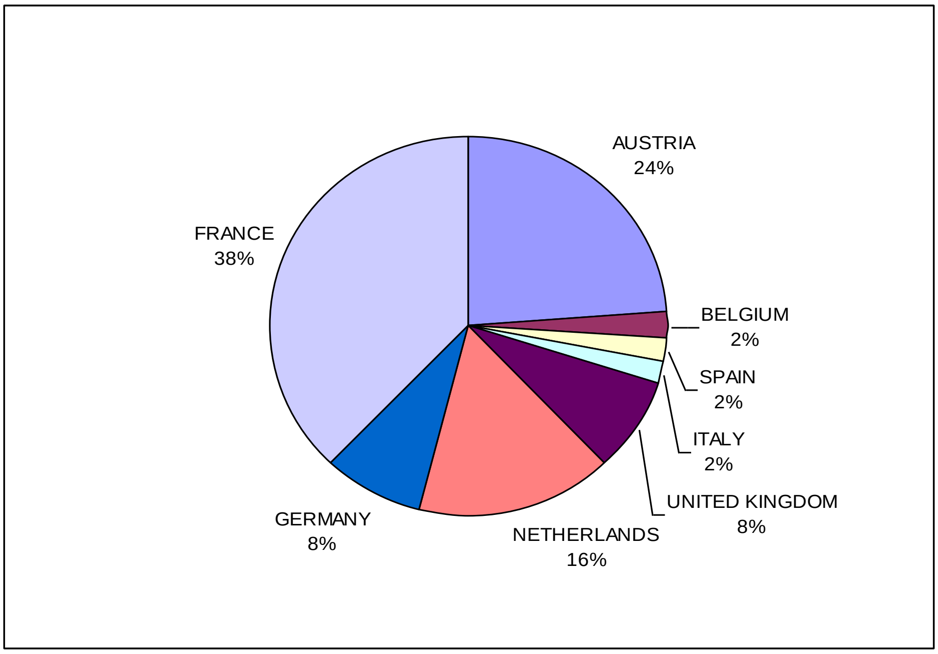

Figure 2 Share of EU total REEs imports (Oko-Institute, 2011).

In 2007, China's demand for REEs was estimated that will reach its production level by the year 2012, (Hurst, 2010a). This is pictured in Figure 3.

In 2008, China started to quote its REEs exports. As a result, in 2010 China's REEs exports rates were decreased by 29% compared to 2008, (Oko-Institute, 2011). China has been restricting the supply of its REEs exports since 2004 at average rate of 13% per year, (ABN AMRO, 2011).

In 2010, the US Department of Energy (USDoE) assessed several critical minerals used in four clean energy technologies: wind turbines, electric vehicles, solar cells and energy efficient lighting. The assessment combined the importance of minerals to the clean energy economy and supply risk with respect to each mineral, (USDoE, 2010).

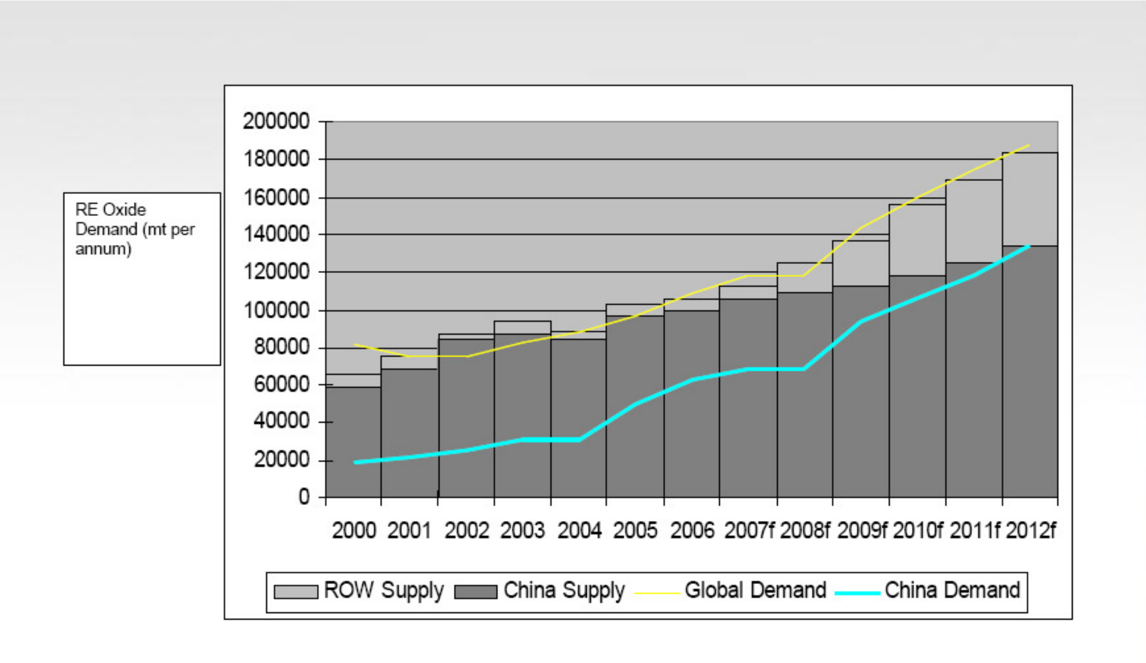

Figure 3 China's demand for REEs estimated in 2007 [Source: Molycorp Minerals presentation slide during 2009 Minor Metals and Rare Earths Conference, accessed from: (Hurst, 2010a)]

The assessment methodology that was used, it was adopted from the US National Academy of Sciences, (USDoE, 2010; Bauer, 2011; USNAS, 2008). The supply risk assessment identified five Rare Earth Elements (terbium, neodymium, dysprosium, yttrium, and europium) whose criticality is considered highest in the short term (0-5 years) and in the medium term (5-15 years), (Figure 4).

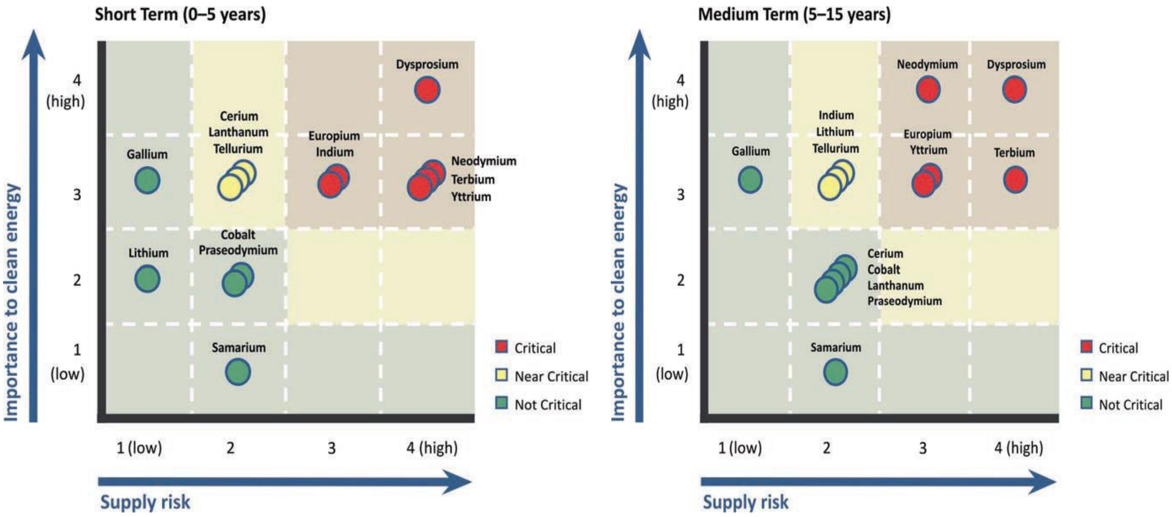

Figure 4 Short-term and medium-term criticality of some REEs, (USDoE, 2010)

2.3.2 Prices and Types of Products Sold

The types of REEs mining products traded worldwide are divided into two categories depending on their physical characteristic: metals and oxides. In addition, they are divided in terms of purity.

Table 3 describes the percentage (%) scale of metals purity in terms of parts-per-million (ppm), (Ames Lab, 2014).

Table 3 Purity scale in terms of parts-per-million (ppm) of matter (Ames Lab, 2014)

Purity %	Total Parts	Matrix ppm	Impurity ppm
90%	1,000,000	900,000	100,000
99%	1,000,000	990,000	10,000
99.9%	1,000,000	999,000	1,000
99.99%	1,000,000	999,900	100
99.999%	1,000,000	999,990	10
99.9999%	1,000,000	999,999	1
99.99999%	1,000,000	999,999.9	0.1
100%	1,000,000	1,000,000	0

For example, in a 99.99% purity of Neodymium, for every million atoms of matter, 999,900 of the atoms are Neodymium atoms with 100 atoms of other elements.

The graph of Figure A1 of Appendix A describes the basket price evolution of ten rare earth elements between years 2009 and 2016 (source: Arafura Resources Limited). Prices are in US dollars ($).

According to the US Geological Survey (USGS, 2008), the following are the main contributing factors that affected prices of REEs the last decades:

- Dissolution of the USSR in 1991 depressed the price of metals.
- Growth of China’s economy starting in about 1998 coincided with rising metals prices.
- Commodity-specific events, such as mine closure or low stocks, caused variations on the larger trends.

REEs are not traded in markets or metal exchanges like other minerals, but they are sold through private own companies. In some case they are sold in black market as products from smuggling.

2.3.3 Geopolitics

The most characteristic phrase which emphasizes the importance of REEs was stated in 1992 by the Chinese leader Deng Xiaoping: "*There is oil in the Middle East; there is rare earth in China*". In 1999, another Chinese leader, President Jiang Zemin, also highlighted the significance of REEs and their contribution for China's economic superiority. In China, the development of REEs mining and industry is considered to have a relationship to modern military technology, (Hurst, 2010b). Paradoxically, although China is currently the dominant player in REEs global mining production, yet, the main effort of China's search for global resources is to confine additional REEs from elsewhere to maintain economic growth, (Caceres and Ear, 2012). In the former Soviet Union REEs were considered a national secret and very limited information was released due to their application to USSR's defense systems, (Hurst, 2010b). In accordance with the European Union, a raw material is labeled "*critical*" when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials. REEs are considered critical raw materials in the EU, (EC, and 2010a). The US approach is based on different facets of criticality: importance in use, availability and in some cases dependency to national security and economy since the U.S. government raised concerns regarding access to defense critical resources, (Oko-Institute, 2011; USGAO, 2010; Burgess, 2010).

Some minerals are also called "*strategic*" whenever their location is concentrated in vulnerable or unfriendly places and when they are essential to production of military hardware. Strategic minerals have become the lifeblood of the military-industrial complex, (Plotkin, 1985). In that manner, REEs may also be considered strategic materials. A geopolitical analysis stated: "*The Rare Earth Elements are as strategic a commodity as crude oil or food, and will be for the rest of this century*", (ABN AMRO, 2011). Access to REEs is becoming a geopolitical scramble with multiple players and new opportunities arise for miners of REEs, (Control Risks, 2011).

An event that occurred in September 2010 has changed the global status on the market of REEs and actually showed the major impact of REEs to global political thinking: a Chinese cargo ship collided with two ships of the Japanese coastguard. The Japanese arrested the

Chinese captain. The Chinese Government announced retaliation measures and declared that will not supply in future Japan with REEs (embargo), (Der Tagesspiegel, 2010). For some US journalists, this situation was compared to the 1941 American oil embargo to Japan (this action is quoted as one of the causal factors that Japan afterward attacked Pearl Harbor), (New York Times, 2010).

In October 2011 the German Chancellor Merkel visited Mongolia "at a time when Europe's debt crisis was hotter than ever". This was a historic first time visit ever of a German Chancellor in Mongolia. The underlying reason of this visit was the search of the German government for raw materials, and more specifically, of REEs, (Spiegel On Line International, 2011).

In March 2012 the US, Japan and the European Union have filed a case against China at the World Trade Organization, challenging its restrictions on rare earth exports, (WTO, 2012a, 2012b, 2012c). These are the first WTO cases to be filed jointly by the US, EU and Japan. US President Barack Obama accused China of breaking agreed trade rules as he announced the case at the White House, (BBC News, 2012). The number of Global Geopolitical Events and Reports Related to REEs between the years 2010 and 2012 is shown in Tables 4 and 5 respectively. It should be noted that China's global strategy is to restrict as many as possible REEs ores/reserves (Cáceres and Ear, 2012; Power and Mohan, 2010; Lyman, 2006; Reuters, 2012).

Table 4 Global Geopolitical Events Related to REEs (2010-2012)

Year	Country/organization	Event
2010	China – Japan Governments	China announced retaliation measures against Japan (ban/embargo of Chinese REEs exports to Japan)
	Columbia University, School of International & Public Affairs (SIPA)	Creation of academic course specifically dedicated to REEs research (3 academic credits). Full Course Title: "Citigroup, Global Commodities Research: Political and Economic Impact of Rare Earths", Course Number: SIPA900.032
	German – Mongolian Governments	First time visit of German Chancellor to Mongolia. Reason for visit: REEs trade agreement.
	EU – Japanese – US - Chinese Governments	US, Japan and the EU Governments filed a case against China at the World Trade Organization challenging its restrictions on REEs exports.
	US Government	US President Barack Obama accused China of breaking agreed trade rules on REEs during a Press Conference at the White House.

Table 5 Global Geopolitical Reports/Documents Related to REEs (2010-2012)

Year	Country/Organization	Report / Document (*)
2010	US Air War College, US Air Force	"Sustainability of Strategic Minerals in Southern Africa and Potential Conflicts and Partnerships"
	US Institute for the Analysis of Global Security (Non-profit Think Tank)	Report: "China's Rare Earth Elements Industry: What Can the West Learn?"
	US Army, Foreign Military Studies Office	Report: "China's Ace in the Hole: Rare Earth Elements"
	The Hague Centre for Strategic Studies (HCSS - Independent Think Tank - Netherlands)	Report: "Rare Earth Elements and Strategic Minerals Policy"
	Organization for Economic Cooperation and Development (OECD)	Report: "Export Restrictions on Strategic Raw Materials and their Impact on Trade and Global Supply"
2011	US National Defense University, Joint Forces Staff College	Master thesis: "Mining and Exploitation of Rare Earth Elements in Africa as an Engagement Strategy in US Africa Command"
	US Army College	Master thesis: "An Integrated Rare Earth Elements Supply Chain Strategy"
	ABN AMRO (Financial Institution, Netherlands)	Report: "Geopolitical Analysis: Rare Earth Elements Risk Analysis"

(*) all documents can be freely downloaded

2.3.4 Initiatives

During this investigation several REEs-related initiatives have been identified since 2010. These are shown in Tables 6 and 7.

2.3.5 Mitigation

A number of mitigation techniques have been proposed in order to reduce the supply risk of REEs. These techniques are divided into substitution and reuse/recycling/waste reduction. These techniques are shown in Table 8.

Table 6 REEs Initiatives in US and EU (2010-2012) - Regulatory Initiatives

Year	US	EU
2010	• US Congress, The Senate Energy & Natural Resources Committee Subcommittee on Energy, "Hearing of Dept. of Energy Assistant Secretary for Policy & International Affairs" • US Congress, House bill: "H.R. 6160, Rare Earths and Critical Materials Revitalization Act" • US Congress, House bill: "H.R. 4866, the Rare Earths Supply-Chain Technology and Resources Transformation Act" • US Congress, Senate proposal: "S. 3521, Rare Earths Supply Technology and Resources Transformation Act"	
2011	• US Congress, Proposed House and Senate of defence authorization bill: "P.L. 111-84, the Fiscal Year 2010 National Defence Authorization Act" • US Congress, House bill: "H.R. 5136, the Fiscal Year 2011 National Defence Authorization Act" • US Congress, House bill: "H.R. 1388, Rare Earths Supply Chain Technology and Resources Transformation Act of 2011 (RESTART Act)" • US Congress, House bill: "H.R. Rare Earths and Critical Materials Revitalization Act of 2011" • US Congress, House bill: "H.R. 2184 Rare Earths Policy Task Force and Materials Act" • US Congress, House bill: "H.R. 1314: RARE Act of 2011" • US Congress, Senate proposal: "Critical Minerals Policy Act of 2011" • US Congress, Senate proposal: "S. 1113 Critical Minerals Policy Act of 2011" • US Congress, House bill: "Energy Critical Elements Renewal Act of 2011"	
2012		• European Commission, Proposal: "Innovation Partnership to Overcome Europe's Raw Materials Shortage"

Table 7 REEs Initiatives in US and EU (2010-2012) - Other Initiatives

YEAR	US	EU
2010	• US Government Accountability Office, Report: "Rare Earth Materials in Defense Supply Chain", • US Congressional Research Service, Report: "Rare Earth Elements: The Global Supply Chain" • US Department of Energy, Report: "Critical Materials Strategy" • US Department of Interior, Geological Survey (USGS), Report: "The Principal Rare Earth Deposits of the United States –A Summary of Domestic Deposits and a Global Perspective"	• European Commission, Enterprise and Industry, Report: "Critical Raw Materials for the EU"
2011	• US Congressional Research Service, Report: "REEs in National Defence: Background, Oversight Issues, and Options for Congress" • US Congressional Research Service, Report: "REEs: The Global Supply Chain" • US Department of Defence, National Defence University, Joint Forces Staff College, Master's Thesis: "Mining and Exploitation of REEs in Africa as an Engagement Strategy in US Africa Command" • US Department of Defense, US Army War College, Master's Thesis: "An Integrated Rare Earth Elements Supply Chain Strategy"	• European Commission, Joint Research Center (JRC), Institute for Energy and Transport, Report: "Critical Metals in Strategic Energy Technologies" • Green Party of the European Parliament, OKO Institute, Report: "Study on Rare Earths and Their Recycling"

Table 8 REEs Proposed Mitigation Techniques

Substitution	Reuse, Recycling &Waste Reduction
Reduction of neodymium and dysprosium usage in existing magnetic materials, (EC, 2010b; Oakdene Hollins Ltd, 2010). New or alternative magnetic materials. Currently there is no evidence of any successful developments towards new materials which can compete or better the strength of neodymium based magnets. Many experts believe that no such materials exist, (EC, 2010b; Oakdene Hollins Ltd., 2010). Technology choice. For example, there are gear-based wind turbines with and without permanent magnets, (EC, 2010b; Oakdene Hollins Ltd., 2010). REEs are used in approximately 14% of newly installed wind turbines. A supply shortage of REEs would lead to a shift to alternative turbine types, (Oko-Institute, 2011). No feasible replacement for the REEs magnets used in EV motors has been discovered. Minimisation of REEs in existing magnets will only result in small reductions in material usage compared with the overall demand, (Oakdene Hollins Ltd., 2010). Electric motors which do not require magnets are the most likely way of reducing or eliminating Rare Earth in EV magnets. However, for technical reasons Rare Earth technology is favoured in the current generation of hybrid vehicles, (Oakdene Hollins Ltd., 2010).	There is a potential to recycle neodymium and dysprosium from pre-consumer magnets, although R&D of the recycling technologies is required, (EC, 2010b; Oakdene Hollins, 2010). For post-consumer waste, the best opportunities lie within recycling the magnets contained within hard disc drives, (EC, 2010b; Oakdene Hollins Ltd., 2010). Further research in this area is needed, (EC, 2010b; Oakdene Hollins Ltd., 2010). Several constraints for a wider recycling of REEs exists: the need for an efficient collection system, the need for adequate high prices, he long life of products such as vehicles and wind turbines, (Oko-Institute, 2011).

Substitution	Reuse, Recycling &Waste Reduction
A simple substitution of a REEs compound by another compound is a quite rare case, (Oko-Institute, 2011). Substitutions of REEs used in energy efficient lighting systems are rare. Substitutions of REEs used in automotive catalysts and catalysts for petroleum refining are rare, (Oko-Institute, 2011). The use of nanotechnology is being considered, (Oko-Institute, 2011).	

Chapter 3. Stream Mapping of REEs Production Process

The REEs mining is characterized by two basic attributes. The first attribute is the presence of thorium and/or uranium in almost all REEs-bearing ores (Long et al., 2010). Bastaesite, xenotime and monazite are the principal mineral ores most feasible for the extraction of REEs. Monazite contains 0.2%-0.4% uranium and 4.5%-9.5% thorium. Bastaesite contains 0.1%-0.2% thorium. Xenotime contains 0.81% of uranium and 0.83% of thorium, (Pillai, 2007). This attribute is straightforward associated to unwanted radioactivity. The second attribute is originated by the term “Elements” itself: when we are referring to REEs, we actually refer to fifteen different elements, so, it is uncommon to find identical REEs ores and it seems to be a lack of a standardized procedure for the extraction and refining of REEs (Long et al., 2010).

Stream mapping would be considered the tool which pictures the activities of a mining company in a sequence of information, and/or materials and/or actions in order to design and/or order and/or produce and/or deliver products to customers (MacInnes, 2002). A stream map would be the first step of in order to deliver value in terms of efficiency and effectiveness to meet fiscal demands and provide a safe workplace. The information regarding stream mapping of REEs mining processes is limited due to the following reasons: first, China is the dominant producer of REEs and there is a lack of data regarding REEs production processes in that country. Second, a large number of Chinese REEs are produced in illegal mines which afterward are smuggled abroad. In fact, it has been estimated that smuggling accounted for one-third of the total volume of rare earths exported from China. It is claimed that smuggling indicates a lack of Chinese Government’s control over the Chinese REEs industry and may lead to serious environmental damages (Hurst, 2010a) and (Nicoletopoulos, 2012). Third, the mining sector of REEs in other industrialized countries was not existed until recently. Figures 5, 6, 7, 8, 9 and 10 show different REEs processing flow sheets. Taking into consideration these process flow sheets a generic REEs stream map was created which is shown in Figure 11. The mining processes of REEs ores does not differ from any other hard-rock mining processes. Most common deposits are mined by surface “open pit” mines and/or underground mines. Crushing and grinding of hard rock deposits are processes that lead to mineral beneficiation via floatation. After flotation, the mineral concentrates are further processed chemically and mixed REEs compounds are extracted. The individual REEs compounds are obtained after purification while final products require further treatment. The scope of stream mapping is to only provide the big picture and is not focusing in detailed description of the processes.

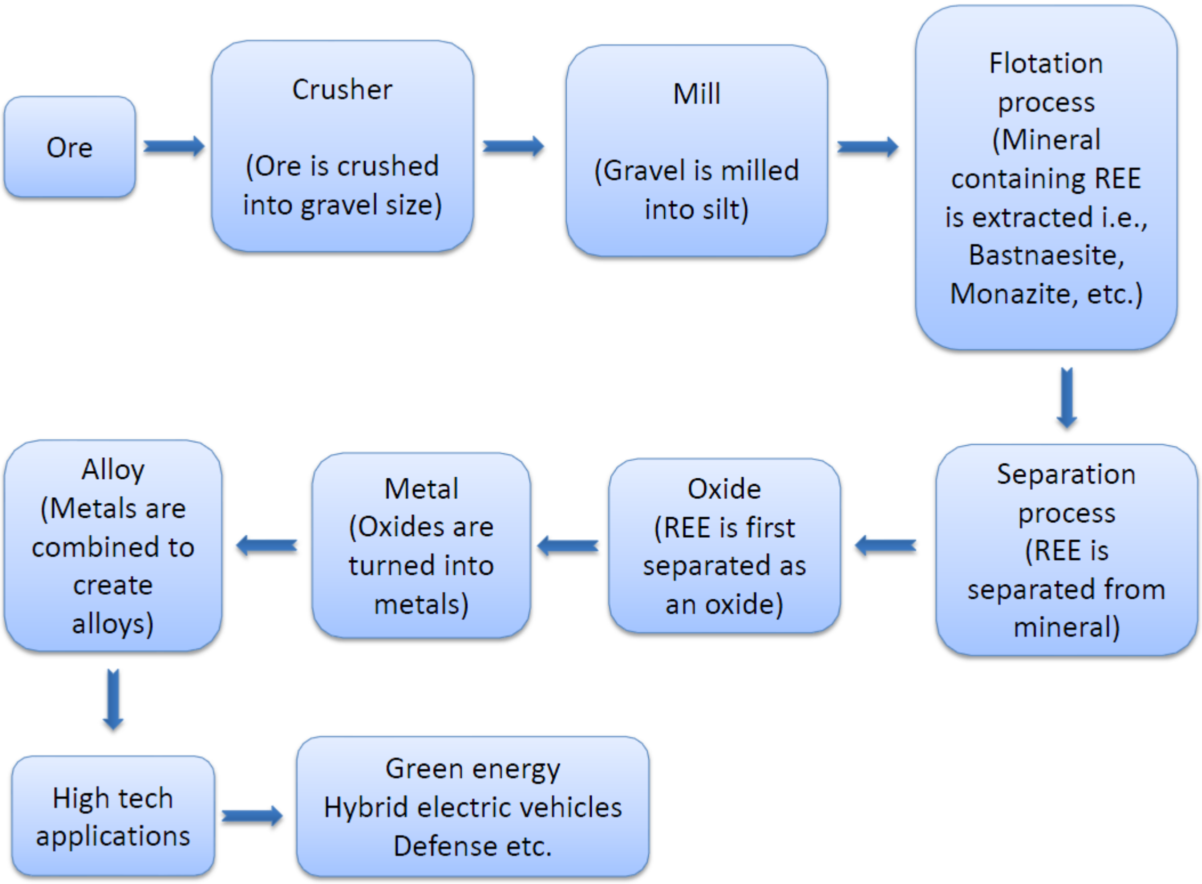

Figure 5 Flowchart depicting the mining and processing of REEs (modified from US EPA, 2011)

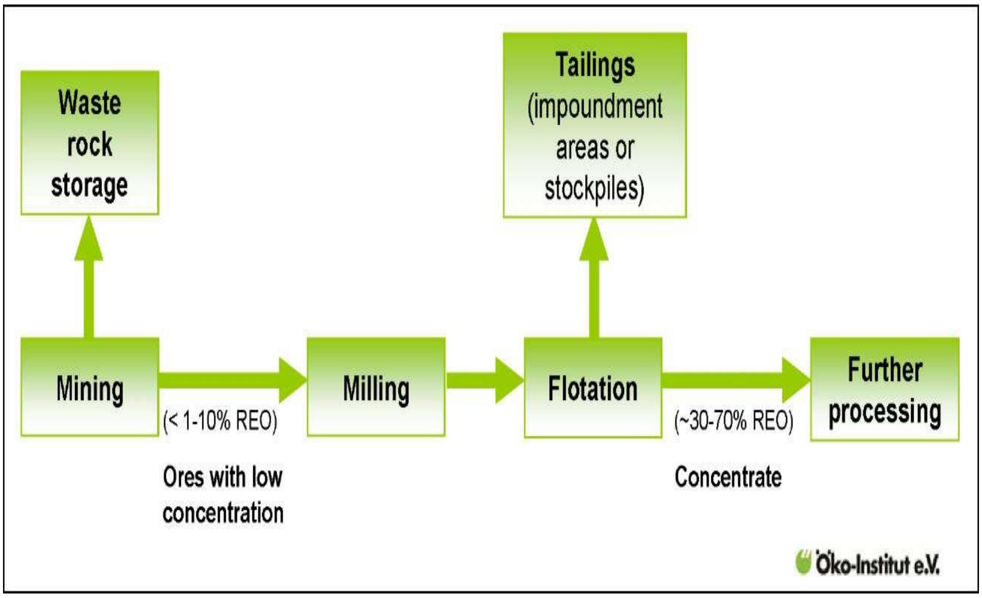

Figure 6 Main process steps in mining and processing of REEs (Oko-Institute, 2011)

The US Council of Foreign Relations (US CFR) presented a general two-phase REEs production model (Figure 7).

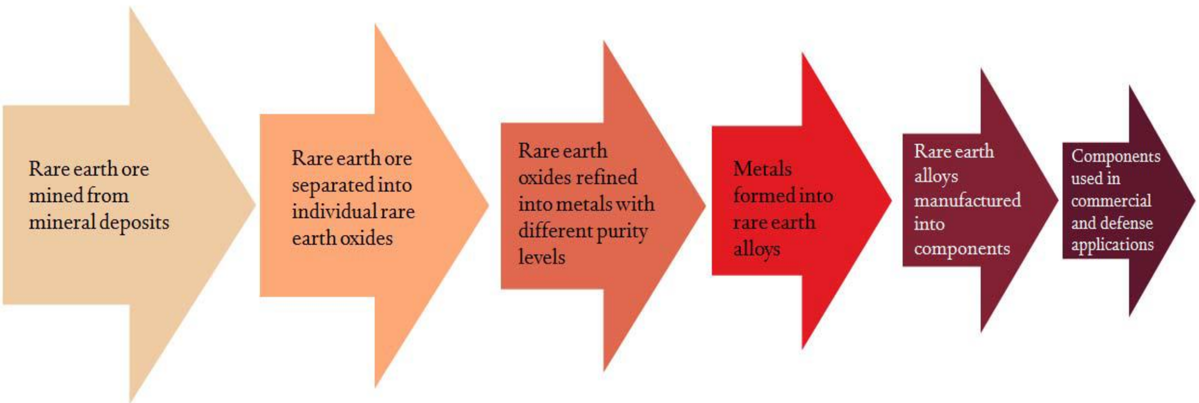

Figure 7 Main Processing and Production Stages for REE Materials (Source: US CFR, 2014)

Figure 8 presents the first generation of an in-situ leaching technology that was developed by Chi et al. (2013). REEs are leached with sodium chloride in the first-generation leaching technology, firstly by barrel leaching and then developed into bath leaching.

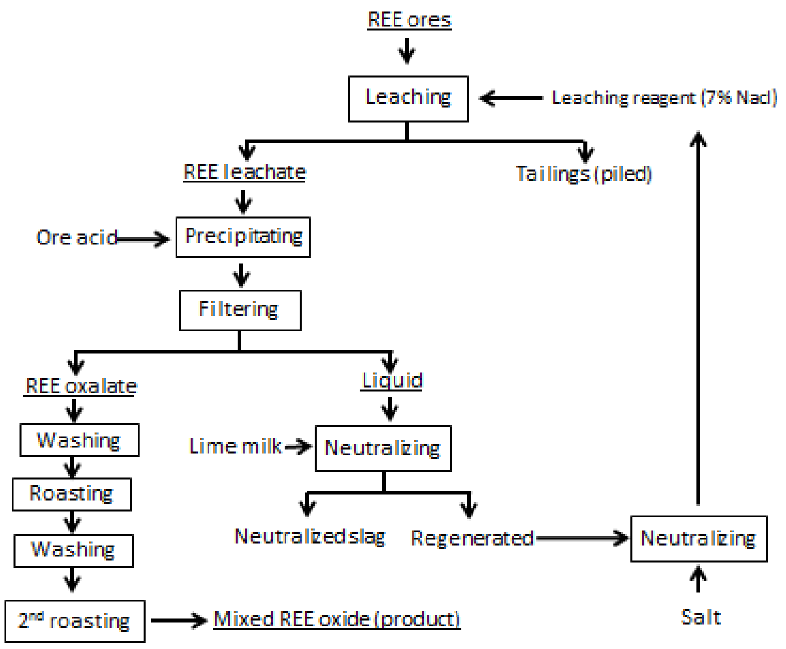

Figure 8 Flow process diagram of the first generation NaCl leaching technology (Source: Chi et al., 2013)

Figure 9 presents a monazite flow sheet using magnetic separators adopted at Indian Rare Earth Limited (Asnani and Patra, 2013).

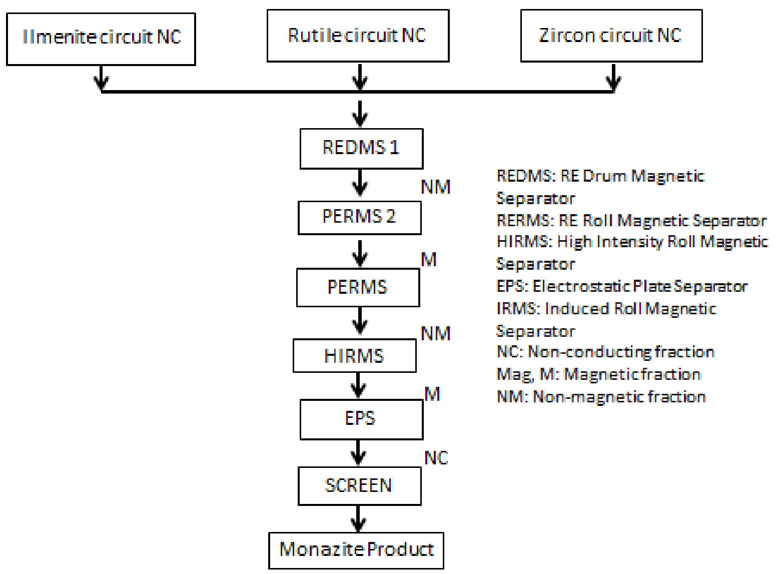

Figure 9 Monazite flow sheet using magnetic separators

Another illustrative flow sheet for REEs processing is shown in Figure 10 (Guan et al., 2013).

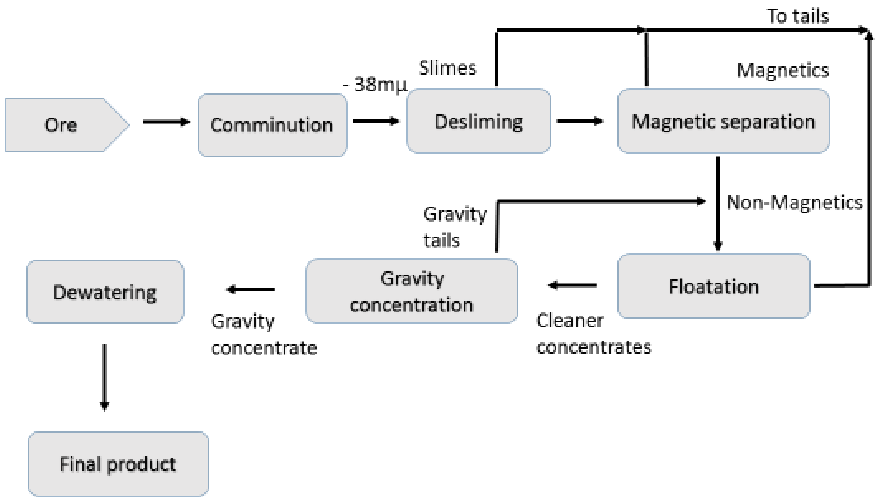

Figure 10 Overview of Necholacho flowsheet

Several other flow sheets for REEs processing exists in the academic literature. For more details and additional flow sheets readers are prompted/referred to the Proceedings of the 52nd Conference of Metallurgists (2013) and Golev (2014).

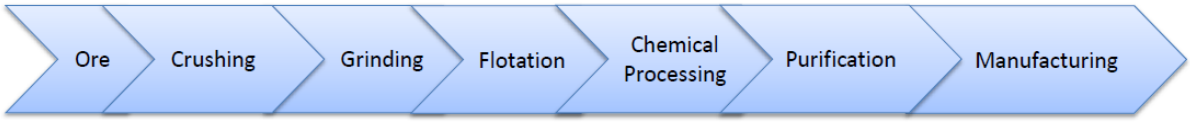

Figure 11 Stream Mapping of Mining and Processing of REEs

Chapter 4. Identification of Stakeholders

Like any other hard rock mining processes, mining of REEs would engage the involvement of different stakeholders ("players") in every step of the above stream map. The main stakeholders in the production of REEs are the mining companies, the markets, the public, the governments/NGOs, the employees, and the media (Figure 12). Each stakeholder may affect the final REEs production in a different manner. The fishbone diagram of Figure 13 was developed to represent the "effect" of each stakeholder to the REEs production process. The following sections discuss some of the most worth mentioned "effects" of each stakeholder.

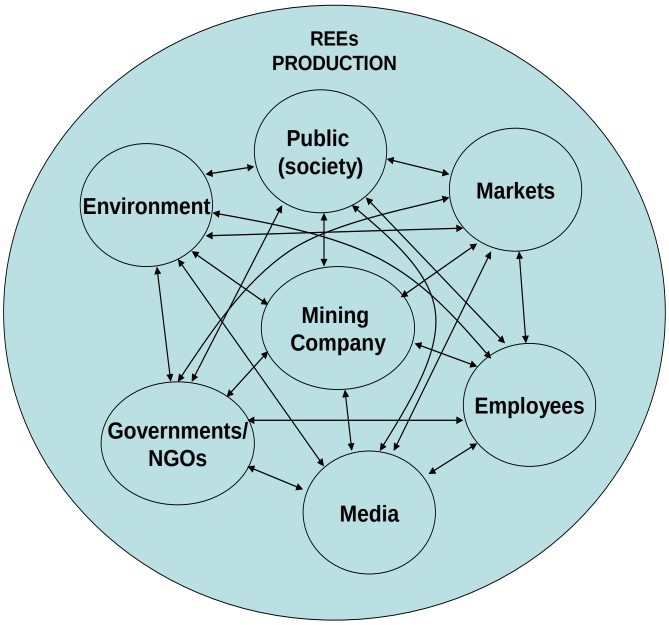

Figure 12 Main stakeholders in REEs production

4.1 Environment

From the environmental perspective, mining of REEs is expected to be similar to any other hard rock mining procedures and of the same significance as other mineral mining operations. It has been mentioned that "except for the radioactivity of uranium and thorium the potential waste emissions would be comparable to a typical hard rock mine" (US EPA, 2012a). Thus, during the development of a roadmap which may provide essential principles/best practices to sustainable mining of REEs special attention should be given to the radiation risk management. Other possible contaminants during REEs mining operations would be barium, beryllium, copper, lead, manganese, zinc, sulfide minerals, carbonate minerals, fluorine and asbestos minerals (EPA, 2011). Tailings would be considered an additional probable environmental risk (Oko-Institute, 2011; IAEA, 2002; IAEA, 2011), but proper design, operation and management of a mine would reduce that risk to acceptable levels (US EPA, 2012a).

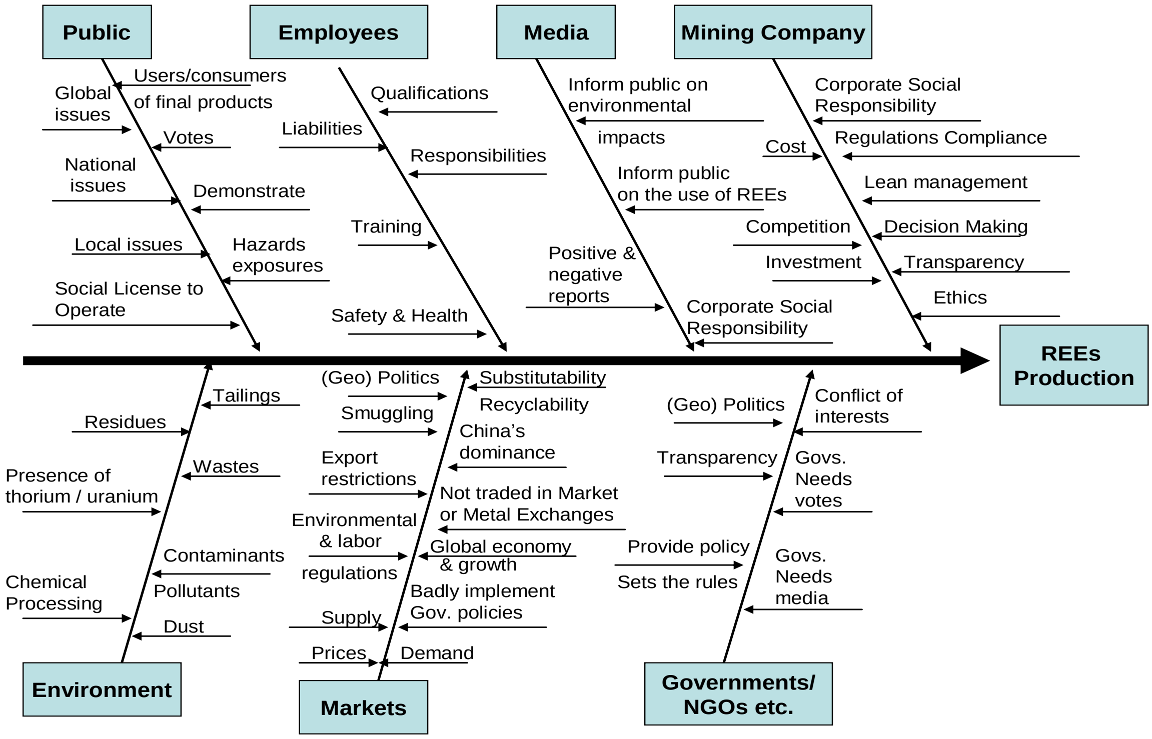

Figure 13 Fishbone diagram representing the "effect" of each stakeholder to the production of REEs

4.2 Public

The social conditions regarding mining have been changed worldwide. The public opinion is very sensitive to any new or existed mining project due to probable environmental risks and public exposures to hazards. The Social License to Operate would be a useful tool which may create a necessary social agreement/"contract" between the mining company and the local and/or national and/or global society (Giurco et al., 2010). Public have two side "effects" in REEs production: is a user/consumer of final REEs products (i.e. electrical cars) and simultaneously have the right to vote. In June 2012, the issue of a new REEs processing plant in Malaysia became the main issue of the national Malaysian elections (ABC Network, 2012).

4.3 Employees

The contribution of employees to the production of REEs would be considered similar to any other hard rock mining operation. Some special considerations would be required while dealing with the issue of radiation. These radiation considerations would be related to occupational safety and health, training, qualifications and responsibilities.

4.4 Media

Media plays a major role as a stakeholder in REEs production. The role of media would be negative and/or positive. The positive effect of media is related to optimistic information provided to public regarding the necessity, importance and linkage of REEs to green economy and to the stoppage of climate change (HCSS, 2010). The negative effect of media to a potential REEs project would be related to distribution of bad news due to a probable mishap and/or environmental impacts.

4.5 Markets

Main factors that affect the market of REEs would be the dominance of China in REEs production, the demand/supply/prices mix, the export restrictions which have been put into place in the past by the Chinese government such as: export quotas, export taxes, Value Added Tax-VAT, production quotas, prohibition of foreign investment in REEs (OECD, 2010), smuggling (Hurst, 2010a, PRC, 2012), badly implemented policies that could bring chaos to global markets (Wantchinatimes, 2010), reluctant and/or complete lack of environmental and labor regulations in China (ABN AMRO, 2011), the strict environmental safety, health and labor regulations in the west (Hurst, 2010a), the status of global economy/growth (Wall Street Journal, 2012), the fact that REEs are not traded through Market or Metal Exchanges, the (geo)politics (Kamenopoulos, and Agioutantis, 2012; Telegraph, 2012), the fact that substitution of REEs is rare and/or impossible and/or in preliminary status, and the fact that the recycling potential of REEs suffers by a number of constraints, (Kamenopoulos and Agioutantis, 2012). In accordance with the Chinese government in the past there was “a divergence between price and value of REEs. Over quite a long period of time, the price of REEs products has remained low and failed to reflect their value” (PRC, 2012). China is encouraging foreign investment in REEs industry: up to date 38 joint ventures between Chinese and foreign companies have been established (PRC, 2012).

4.6 Governments/NGOs

The role of the government in REEs production process is of the same importance as in any other hard rock mining process. Governments set the regulations and provide policies for trading, mining, environmental, public and occupational protection. Since 2010, a large number of REEs-related governmental initiatives have been made globally and a significant number of critical geopolitical events/reports related to REEs occurred. In addition, many commercial intergovernmental transactions related to REEs have been reported the last three years (Kamenopoulos and Agioutantis, 2012). Politicians are elected and governmental decisions are sensitive to public opinion, media and NGOs. Conflict of interests between governments, environmental NGOS and politicians may create a challenging political environment (Kamenopoulos and Agioutantis, 2012; Telegraph, 2012).

4.7 Mining Companies

Mining companies are required to operate in a challenging cost sensitive and competitive environment within a strict regulatory frame. Lean, environmental and sustainable management, in conjunction with ethical policies and transparent business rules should be the rule of thumb for building the roadmap to sustainable mining of REEs. It is worth noted that in the past the combination of strict environmental, safety/health and labor regulations, low prices market environment and bad decision making resulted to the closing of the only mining company outside China in '90s (Molycorp), and the dominance of China in global REEs market for almost two decades.

Chapter 5. Hazards / Vulnerabilities

Based on the Stream Mapping Process and taking into consideration the limited available references (Oko-Institute, 2011; US EPA, 2011; US EPA, 2012a; IAEA, 2011), the hazards / vulnerabilities of REEs production were detected for each process and effected stakeholders (Table 9).

Table 9 Hazards/vulnerabilities of REEs production

Process	Hazard/Vulnerability	Effected Stakeholder
Ore Mining	- Air dust - Mine water/dredge water - Overburden - Waste rock - Heavy metals/acids/fluorides to surface/groundwater - Acid Mine Drainage (AMD) - Turbidity - Radiation - CO_2 emissions - Common Occupational Safety & Health Hazards	Environment Employees Public Mining company Media Governments Markets
Crushing	- Air dust - Radiation - CO_2 emissions - Common Occupational Safety & Health Hazards	Environment Employees Public Mining company Media Governments Markets
Grinding	- Air dust - Radiation - CO2 emissions - Common Occupational Safety & Health Hazards	Environment Employees Public Mining company Media Governments Markets
Floatation	- Tailings - Air dust - Radiation - CO_2 emissions - Heavy metals/acids/fluorides to surface/groundwater/soil - Acid Mine Drainage (AMD) - Turbidity - Volatile Organic Compounds (VOCs) - Common Occupational Safety & Health Hazards	Environment Employees Public Mining company Media Governments Markets
Chemical Processing	- Tailings - Radiation - CO_2 emissions - Heavy metals/acids/fluorides to surface/groundwater/soil - Acid Mine Drainage (AMD)	Environment Employees Public Mining company Media Governments

	- Turbidity - Volatile Organic Compounds (VOCs) - Common Occupational Safety & Health Hazards	Markets
Purification	- Radiation - Air dust - CO_2 emissions - Heavy metals/acids/fluorides to surface/groundwater/soil - Volatile Organic Compounds (VOCs) - Common Occupational Safety & Health Hazards	Environment Employees Public Mining company Media Governments Markets
Manufacture	- Air dust - Radiation - CO_2 emissions - Heavy metals/acids/fluorides to surface/groundwater/soil - Volatile Organic Compounds (VOCs) - Common Occupational Safety & Health Hazards	Environment Employees Public Mining company Media Governments Markets

Chapter 6. Sustainable Development Schematic Models

The definition of Sustainable Development (SD) was established in 1987 by the "Brundtland Commission" (UN, 1987). In 1992, world leaders presented the principles of sustainable development at the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil (UN, 1992). During that conference it was agreed that sustainable development consists of three elements: economic development, social development and environmental protection. A "sustainable path" was described as "one that allows every future generation the option of being as well off as its predecessors" (US NRC, 1994).

It should be firmly emphasized that in today's world there are opportunities and challenges when discussing the positive contribution of mining to sustainable development. This was recognized in 2002 in the World Summit on Sustainable Development (WSSD), held in Johannesburg, SA (UN, 2002a). The Johannesburg summit Plan incorporated minerals for the first time, noting "the contribution of mining, minerals and metals to sustainable development". It called for actions "to address the environmental, economic, health and social impacts and benefits of mining" through the participation of stakeholders, and encouraged the world community to develop sustainable mining practices. During the Johannesburg World Summit on Sustainable Development, it was concluded that "minerals and metals make a major contribution to the world economy and modern societies" (UN, 2002a). In 2012, the United Nations RIO+20 Conference on Sustainable Development (UN, 2012b) acknowledged that "mining activities should maximize social and economic benefits, as well as effectively address negative environmental and social impacts. In this regard, we recognize that Governments need strong capacities to develop, manage and regulate their mining industries, in the interest of sustainable development".

Different schematic models picturing SD elements have been proposed. These elements are depicted as 'pillars', as nested circles, or as overlapping circles (IUCN, 2006) (Figure 14). Criticism exists regarding the size of circles and/or the size of pillars in Figure 13. The main source of criticism is related to the relative size of the circles; the size of each circle may picture the importance of each SD pillar. In accordance to the abovementioned criticism, circles / pillars may not be of equal size. Depending from the point of different viewers, the economy circle/importance can be larger than the circle/importance of the environment ("weak sustainability") or vice versa ("strong sustainability") (Morse and McNamara, 2013).

Unfortunately, the extraction of natural resources has created legacies of unacceptable long-term social and environmental impacts in many parts of the world (Moran et al., 2014). A number of questions regarding the sustainability of mining operations were posed twenty or more years ago (Auty and Warhurst, 1993; von Below, 1993; Alan, 1995; Learmont, 1997; James, 1999), while Humphreys (2001) discussed whether the mining industry can afford sustainable development. Questions have also been raised about the oxymoron of sustainable mining, i.e., how mining of non-renewable resources can be viewed in balance to environmental quality, economic growth and social stability (Joyce and Smith, 2003; Rajaramet al., 2005; Horowitz, 2006; EngineersAustralia.org, 2014; Whitmore, 2006).

At the same time, members of the academia have developed sustainable development frameworks applicable to the minerals industry in order to help the decision making process and in an attempt to overcome the negative criticism. Two are the main characteristics of these frameworks: first, all these frameworks are based on the three pillar SD model which includes the environment, the economy and the society. Secondly, "it takes a lot of time to understand where they overlap, do not overlap, and all that needs to be done to comply with the ones we are committed to" (Fitzpatrick et al., 2011). Azapagic (2004) presented a framework for mining sustainability indicators as a tool for performance assessment and improvements. Shen et al. (2015) proposed a sustainable development framework in the context of mining industries based on an Analytical Hierarchy Process, while Hilson and Basu (2003) proposed a framework of sustainable development for the mining sector based on good governance.

In addition to the abovementioned academia based frameworks, inter/intra-governmental initiatives have introduced policy oriented frameworks for the sustainable development in the mineral industry. The International Council on Mining and Metals (ICMM), which was founded in 2001 to improve sustainable development performance in the mining and metals industry, developed 10 principles for sustainable development, which company members are required to implement (ICMM, 2014). The Intergovernmental Forum (IGF) on Mining, Minerals, Metals and Sustainable Development proposed in 2010 a mining policy framework to enhance support towards capacity building that promotes the good governance of the mining/metals sector and its contribution to sustainability (IGF, 2010). The government of India in 2011 adopted the Sustainable Development Framework for the Indian Mining Sector (Indian MoM, 2011). Additional alternate approaches of SD frameworks that may be applicable in the minerals industry are discussed by Fonseca et al. (2013).

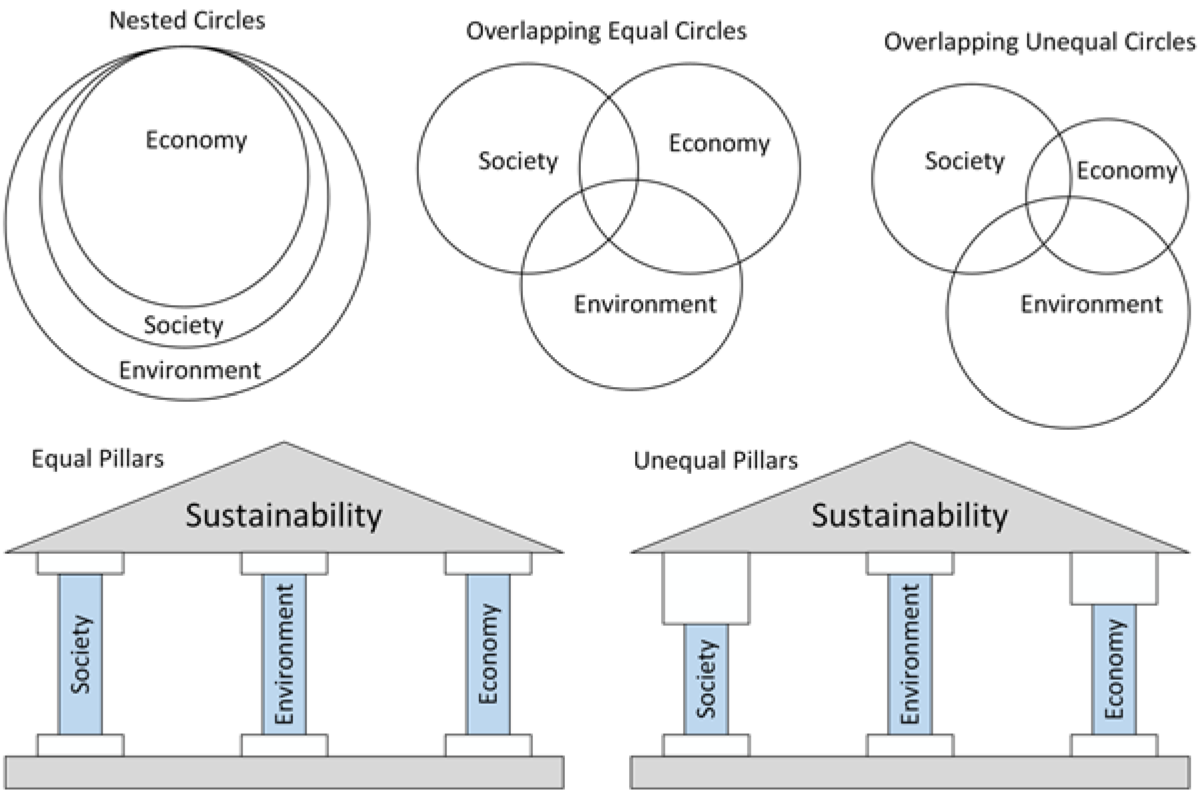

Figure 14 Different Description Models of Sustainable Development

6.1 A Framework for the Sustainable Development of Rare Earth Elements Mining Projects

Recognizing the need to move forward and develop REEs mining projects in a sustainable manner, a framework for the SD of REEs mining projects is proposed in this chapter. The work below specifically refers to the development of REEs mining projects. However it can also be applied to general mining projects. This framework is based on the concept of the “overlapping circles”, where the classic three-circle schema is complemented with more sustainability circles as well as a number of controlling/limiting factors/challenges that interact with or within the circles. Mining of REEs has a long unpleasant history of environmental damage. The Mountain Pass mine in California was shut down due to severe environmental degradation (Ali, 2014). In China, illegal mining is a critical issue (Hayes-Labruto et al., 2013). Environment, let alone social issues, are virtually absent at these mines. China has vowed repeatedly to shut down these mines (PRC, 2012). Any recommended action for the establishment of a sustainable mining framework should be within the context set off by the “Brundtland Commission”, the Rio Summit (AGENDA 21), the WSSD and Rio+20 recommendations. The proposed framework for the SD of REEs mining projects includes fundamental elements that contribute to a holistic sustainable platform. This aims to address the challenges faced during the development of the minerals sector (Kamenopoulos and Agioutantis, 2013; MMSD, 2002) and in particular during the development of REEs mining projects. More specifically the proposed framework includes the following parts (Figure 15):

- √ Five components represented as circles: economy, society, environment, technology, and (geo)politics.
- √ Three controlling/limiting factors: policy, governance, and stakeholders.
- √ A number of output quantities to be used in decision making: indicators

The recommended framework pictured in Figure 15 has a global application. The first three components (economy, society, and environment) were developed by the "Brundtland Commission" in 1987 and they are considered the main pillars of global Sustainable Development (UN, 1987). The component of technology is a key concept of SD: it may resolve the economic, social and environmental problems that make current sustainable development paths unsustainable (UN, 2002b). Technology of extracting and processing REEs is complex especially when secondary streams are used as raw materials and when REEs are extracted with other metals and then separated. Understanding the technology will have an impact on the views of several stakeholders, especially the not experienced ones, such as the public, the regional authorities, the NGOs and the press. The REEs are mostly used in high-tech end products; in some cases these products including hybrid/electrical vehicles, wind turbines, and fluorescent light bulbs, are directly related to the goals of global SD. As a result, the technology should undoubtedly be considered a component of any suggested framework of SD of REEs mining/processing projects. In a similar way, the component of geopolitics may be considered as a must in any suggested SD framework since the REEs are considered strategic minerals. The most characteristic phrase which emphasizes the geopolitical importance of REEs was stated in 1992 by the Chinese leader Deng Xiaoping: "There is oil in the Middle East; there is rare earth in China". A geopolitical analyst stated: "The Rare Earth Elements are as strategic a commodity as crude oil or food, and will be for the rest of this century" (ABN AMRO, 2011). Domination of a small number of countries over the supply of REEs may lead to disruption and conflicts between global stakeholders. It is for these reasons that geopolitics is an inevitable component of any framework for the SD of REEs mining/processing projects.

The three controlling/limiting factors of the proposed framework are related in a counterclockwise manner (Figure 15) and this internal process can be considered as a closed loop. Governance is the “sum of the many ways individuals and institutions, public and private, manage their common affairs” (UNDP, 2012). Governance is based on the achievement of preset objectives that best fits the needs of societies, influenced by complex (geo)political scenarios, which affect the environment and the economies. In order to meet the objectives, governance designers utilize specific tools (regulations/laws/rules) that ultimately lead to the formation of policy. Policy is not a static notion: it is adjusted under the specific fluctuating conditions and needs of stakeholders. Stakeholders receive the feedback from the implemented governance; the adjusted policies lead toward the adjustments of governance/supervision and so forth.

To better encapsulate the concept of sustainable path, the “Swiss Cheese” model of accidents was adopted and adjusted to the scope of this analysis (Figure 16, left). Reason’s “Swiss Cheese” model has been proved to be a very useful tool in “accident” analyses: every “accident” is a result of “unsafe acts” created by decision makers and/or latent conditions (Reason, 1990; EUROCONTROL, 2006).

It is now broadly recognized that accidents in multifaceted conditions occur due to multiple interrelated causes. If achieving the application of SD principles for REEs mining project is considered as a desired multifaceted state that may include several latent conditions, then the ideal sustainable path, which produces the most efficient sustainability level without “accidents” should be determined. The concept of an ideal sustainable path for achieving SD during the design and operation of REEs mining projects is presented in Figure 16 (right). This model depicts in the best possible illustrative way the term of “sustainable path”. This model portrays an adjusted form of the "Swiss Cheese Model". The holes in the Sustainable Path’s model shall not be interpreted as the latent conditions of the “Swiss Cheese Model”, but rather as the ideal conditions that if all coincide with each other they will generate the Ideal Sustainable Path: the one that will coincide with all holes.

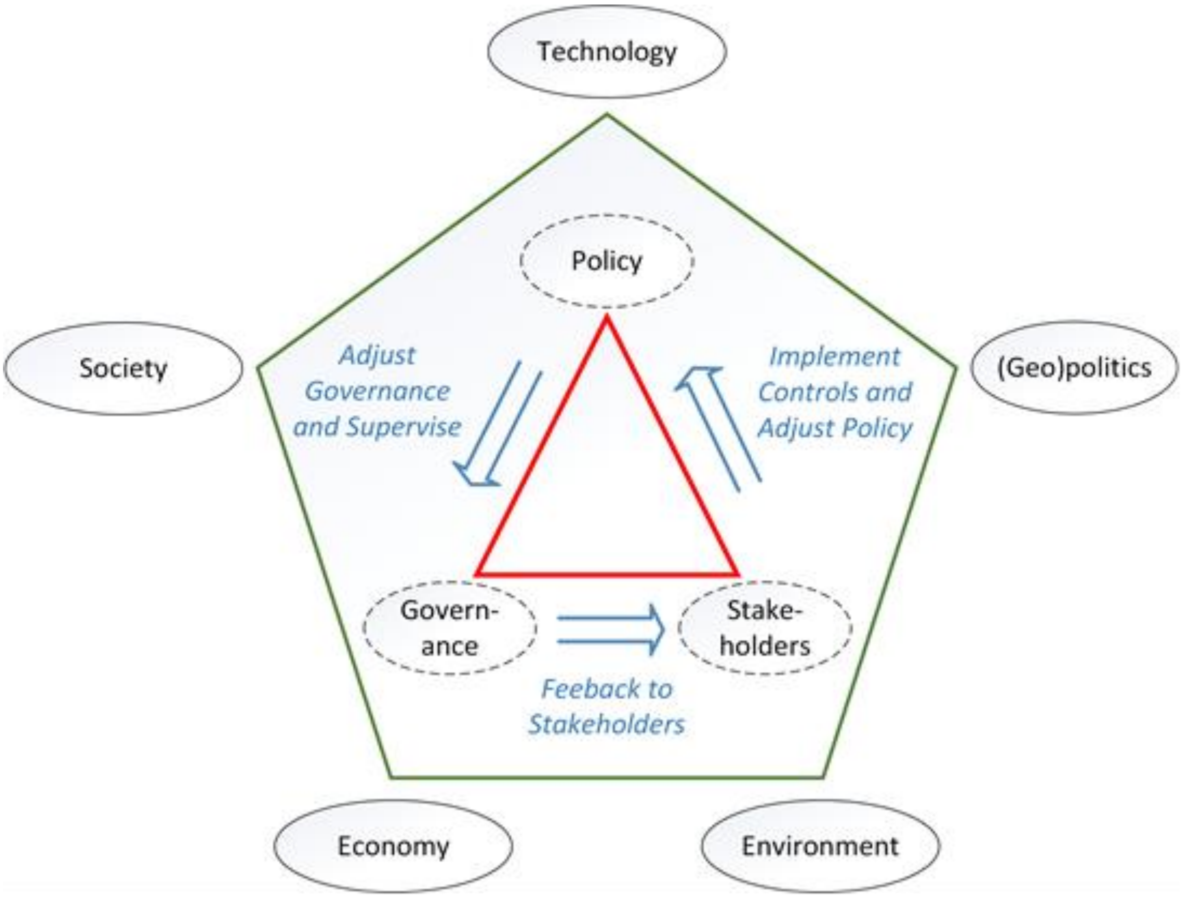

Figure 15 Sustainable Development Framework for REEs Mining and Processing Projects

The SD models pictured in Figure 14 have a significant weakness: it is difficult to quantify each criterion and its contribution to the overall scheme, since the models do not provide a measurable deviation of each probable sustainable metric entity (i.e. indices, ratios, indicators, etc.) from the ideal sustainable path. As a result, there is no meaningful interrelation/interconnection between the elements (circles) of SD and, therefore, decision makers are often faced with fuzzy data sets. To overcome this weakness the circles of sustainability should be examined from a different point of view, i.e., by examining a cross-section as shown in Figure 17.

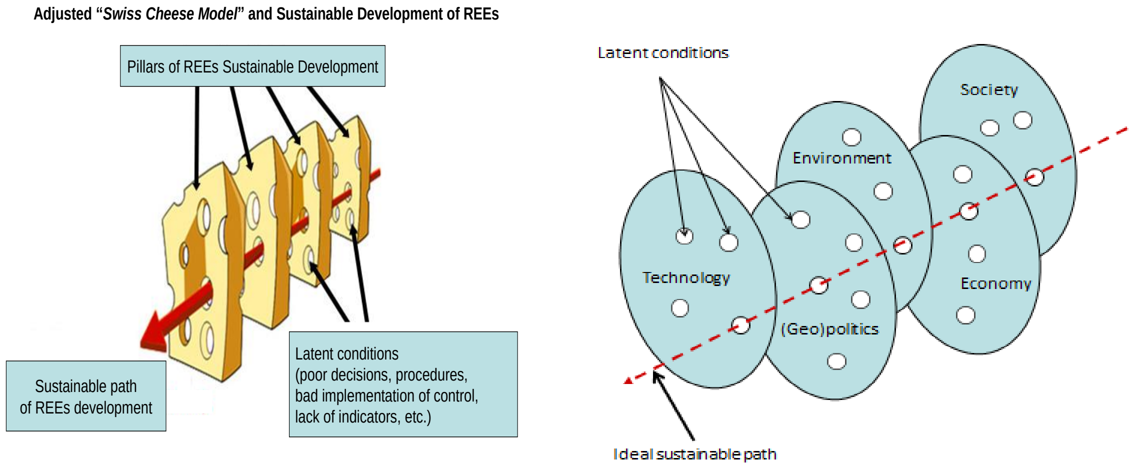

Figure 16 Adjusted "*Swiss Cheese*" and Sustainable Development of REEs mining and processing projects (left) and Ideal Sustainable Path of REEs model (right)

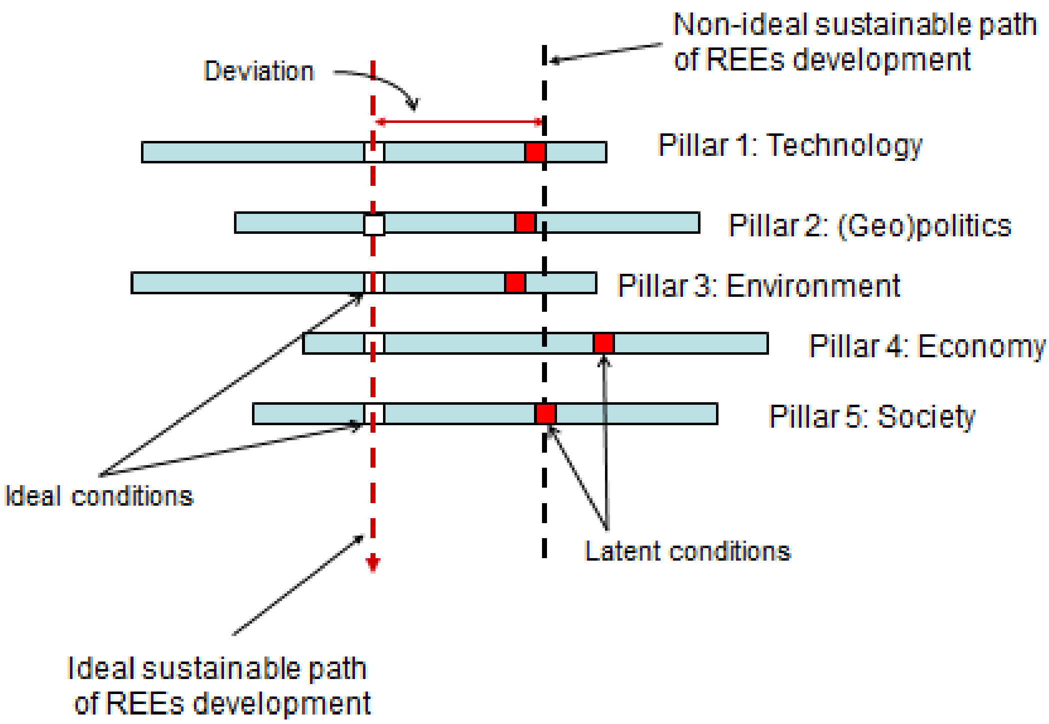

Figure 17 Cross-section of the overlapping sustainability circles/pillar where a common path can be identified

The representation of SD in REEs mining projects has several advantages, since it provides:

a. a better understanding of the SD interrelated elements,

b. a more practical vision of the SD Path,

c. the ability to measure the deviation of probable metric entities from the ideal SD Path,

d. the ability to avoid latent conditions of sustainability, by reducing the deviations and make better decisions that will be closer to the ideal SD Path,

e. the "go-no-go" option by adjusting trade-offs between the different SD elements/metric entities, and

f. the relationships among stakeholders involved in the REEs SD, policy and governance.

6.2 Application of the Generic Framework for Sustainable Development of Mining and Processing REEs

A common expression in management says that "*what gets measured gets done*" (Batterham, 2005). Evaluating REEs mining projects from the sustainability point of view is very critical for decision makers and all stakeholders because it can provide measurable positive or negative impacts of such projects. The best way to perform such evaluations is by using appropriate indicators. Thus, the core of the proposed framework (Figure 14) is based on indicators.

A sustainability indicator can be defined as "…*measurable aspect of environmental, economic, or social systems that is useful for monitoring changes in system characteristics relevant to the continuation of human and environmental wellbeing*...." (US EPA, 2012b). The selection of indicators should be based on the five proposed pillars of Figure 15. The overall process which details how the generic framework can be applied in the case of REEs is presented in Figure 18.

The next step would be the development of a decision support system which will incorporate selected indicators and assist decision makers/stakeholders to better assess the impact of any REEs project from the sustainability point of view.

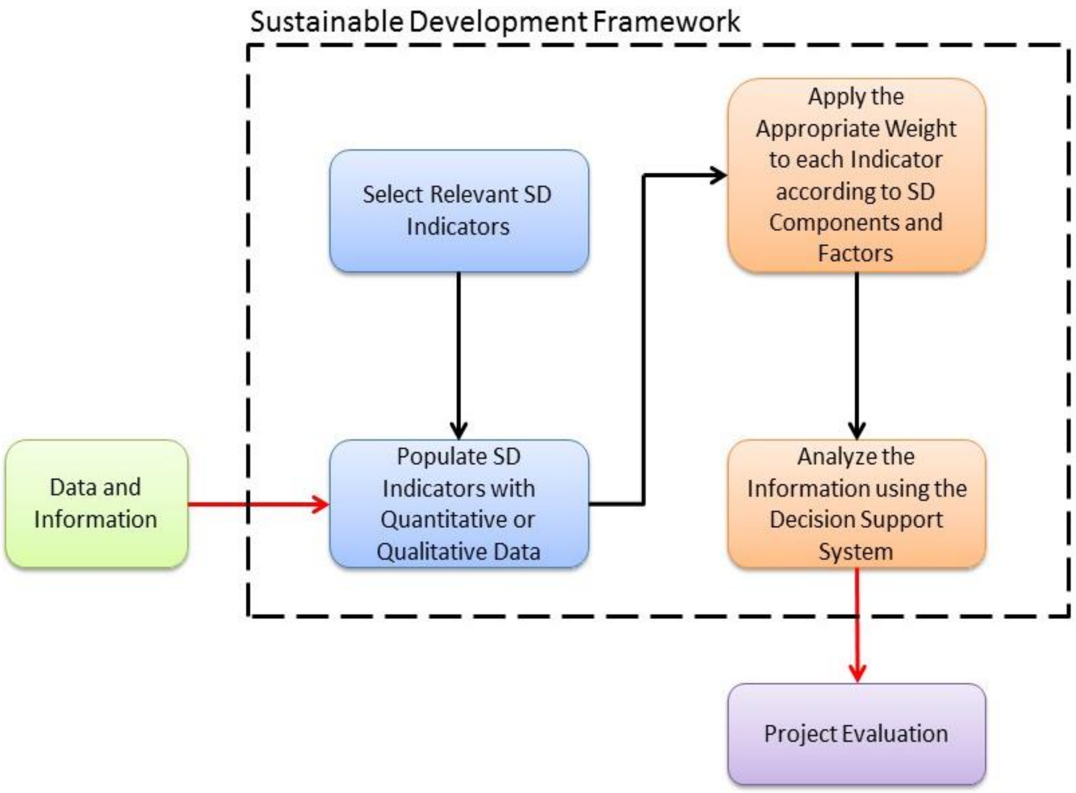

Figure 18 The process which describes how the generic framework can be applied in the case of REEs

Chapter 7: Sustainable Development Criteria and Indicators for the Assessment of REEs Mining Projects

The aim of this chapter is to present a set of supplementary sustainable development criteria and indicators (C&I), developed specifically for REEs mining projects, incorporating the unique particularities that differentiate REEs projects from other mineral mining projects. The format and approach used in the chapter is as follows. First we investigated the current state of art with respect to sustainable development indicators because our goal was to build the proposed C&I upon the foundation of existing criteria and indicator sets, in general and for the mining sector specifically.

C&I are only useful to the degree that they effectively communicate accurate and unbiased information to decision makers and stakeholders. In the absence of such information, the likelihood that new mining operations will be opposed by the general public increases. Conversely, having a set of C&I to adequately inform people about the sustainability contributions of proposed new REEs mines will support more comprehensive analysis of the costs and benefits of individual projects. Additionally, while keeping lines of communication open is important for all mining projects, it is considered especially important in the case of REEs mining projects due to the specific particularities associated with the extraction of REEs. Thus, the literature was investigated on information sharing and social license to operate within the minerals sector. Finally, the hypothesis was that currently available minerals C&I, while useful, are inadequate to capture the full scope of issues related to REEs mining. Analysis of the technical, physical and geopolitical characteristics of REEs was undertaken, which ultimately led to the identification of a set of issues not directly addressed in traditional C&I.

7.1 Sustainability Indicators

Agenda 21, the report of the UN Conference on Environment and Development (Rio Earth Summit) in 1992 recommended that countries develop criteria and indicators of sustainability (UN, 1992). Over the ensuing years numerous indicators of sustainable development (SD) have been proposed at multiple spatial scales (global, regional, national, community). These indicators evaluate different thematic approaches to SD as perceived in different sectors, not necessarily related to the mining industry. For example, the United Nations (UN) has published three sets of indicators of country sustainable development in 1996, 2001 and 2007. The most recent UN publication for country sustainability proposed a set of 50 indicators that were part of a larger set of 96 indicators of SD (UN, 2007). The UN Mediterranean Sustainable Development Strategy proposed a set of 34 priority indicators toward sustainable development in the Mediterranean region (UN, 2005). The US Interagency Working Party Sustainability Indicators proposed a set of 40 indicators relating to a variety of features of sustainability (USIWPSI, 1998). The Organization for Economic Development and Cooperation (OECD) has proposed several categories and numbers of indicators regarding environmental sustainability (OECD, 2003). The UN Economic Commission in cooperation with the OECD and the Statistical Office of the European Union (Eurostat) proposed a set of 28 policy-made indicators and capital-based indicators to assess sustainability in EU countries (UN, 2009). Eurostat also proposed a set of 63 indicators, of which 22 are social, 21 are economic and 16 are environmental (EC, 2001; EC, 2005). It should be noted, however, that although the Eurostat study is considered a good base line approach for SD indicators, it was mainly focused on European countries and was not industry specific.

In parallel industries began developing C&I applicable to various sectors ranging from chemicals to construction to manufacturing. However, it was initially believed that the concept of sustainability did not apply to mining because mineral resources are nonrenewable. This view began to change in the mid-1990s (Shields, 1998). In 1999, nine Chief Executive Officers of some of the world's largest mining companies came together in Davos, Switzerland. Motivated by the fact that a disconnection had emerged between mining/minerals-related practices and the values of modern society, they voiced concern that their "social license to operate" was in jeopardy. The outcome of this meeting was the initiation of the Mining Minerals and Sustainable Development (MMSD) project, the goal of which was to examine the role of the minerals sector in contributing to sustainable development. The project report, Breaking New Ground, provided a comprehensive examination of the mining industry globally at the turn of the century (MMSD, 2002). One of the core objectives of MMSD was to develop a set of practical principles, criteria and/or indicators that could be used to guide or test activities related to the exploration for, and the design, operation and performance monitoring of individual mining operations, existing or proposed, in terms of their compatibility with the concepts or principles of sustainability. In parallel, the MMSD North America regional work group produced the report "Seven Questions to Sustainability," a document that recommended 85 indicators organized under 7 criteria related to mining operations (IISD, 2002).

Despite the comprehensive nature of these criteria, indicators and the recommended process for their use, the 7 Questions approach has not been widely adopted. Rather, in the ensuing years individual mining firms that had decided to publicly report on their operations attempted to create company specific sets of C&I. Academics in many countries also created indicator sets. Many of these were published as part of the Sustainable Development in the Minerals Industry biennial conference series and are available through the Onemine.org website. The result was duplicative efforts and criteria and indicator sets that could not easily be compared.

The International Council on Mining and Metals, itself an outgrowth of MMSD, undertook to collaborate with the Global Reporting Initiative to create a Mining and Metals Sector Supplement (MMSS) (GRI, 2014). The MMSS presents a tailored version of GRI's Sustainability Reporting Guidelines which detail the Reporting Principles, Disclosures on Management Approach, and Performance Indicators for economic, environmental and social issues for the preparation of sustainability reports by organizations, regardless of their size, sector or location. The additional commentaries and Performance Indicators, developed especially for the mining and metals sector, capture the issues that matter most for major mining companies. The GRI Implementation Manual recommends 150 SD indicators based on 18 criteria with explanations on how to apply, prepare, and interpret them (GRI, 2013).

The MMSS has become the most well-known framework providing guidance for reporting organizations in the mining and metals sector. In addition, this framework is the most widely adopted sustainability framework in the mining sector, used by virtually all publicly traded mining firms that produce sustainability reports. In 2011, approximately 95% of the mining companies' reports were based on the GRI framework (Fonseca et al., 2013). However, although most large companies now use GRI's indicators, it is a less than perfect approach because it is a consensus set as opposed to a set created to actually and fully measure what the sustainability contribution of a mine or mining company actually is. Furthermore, there is currently little consistency across firms in how negative information, i.e., environmental or social damage, is reported, with some firms attempting to legitimize negative aspects through carefully chosen wording (Hahn and Lulfs, 2014).

Another framework which indirectly incorporates indicators related to mining projects is the "Equator Principles". The Equator Principles (EPs) are a risk management framework, adopted by financial institutions, for determining, assessing and managing environmental and social risk in projects and is primarily intended to provide a minimum standard for due diligence to support responsible risk decision-making. The relevant thresholds and criteria for application are described in detail in the Scope section of the EP. In 2014 80 Equator Principles Financial Institutions (EPFIs) in 34 countries have officially adopted the EPs, covering over 70 percent of International Project Finance debt in emerging markets (Equator Principles, 2014). Although the “Equator Principles” document does not provide specific indicators, it could be considered as an indicator on its own (Equator Principles, 2013).

The World Bank recommends a set of 10 SD indicators for mining and energy sectors (World Bank, 2014). These indicators are mostly focused on to the energy cost and consumption criteria of mining projects. Valta et al. (2007) and Tzeferis et al. (2013) presented a set of 45 SD indicators based on 11 criteria tailored to the Greek Industrial Minerals/Metallurgical sector. Zhang (2014) proposed a set of 95 health indicators based on 3 criteria related to REEs mining projects. The EU Directorate General Enterprise and Industry (now DG Growth) developed a set of 20 indicators on the impact of non-energy extractive industry in Europe (EC, 2006). These were divided by industry level (13) and member state level (7).

Table 10 summarizes the abovementioned mining related SD frameworks and indicators. All indicators are considered in a general manner and two are targeted for the minerals industry, but not specifically to REEs mining projects.

Table 10 Mining related SD framework/indicators

Framework	Number of Indicators	Type of Indicators
Mining, Minerals and Sustainable Development North America (IISD, 2002)	85	Targeted to mining sector
Global Reporting Initiative (GRI)	150	General (MMSS targeted to mining sector)
Equator Principles	N/A	General
World Bank	10	General
Valta et al. (2007) and Tzeferis et al. (2013)	45	Targeted to the Greek Industrial Minerals sector
EU DG Enterprise and Industry (European Commission, 2006)	20	Targeted to the EU mining sector

7.2 Stakeholder Communication and Social license to Operate

In order for the minerals sector to make a positive contribution to sustainable development, the following are necessary: a stable economy, a balance of social expectations, good two-way communication between stakeholders, and trust (Villas Bôas, et al., 2005). There are two forms of trust: social trust (trust in motives), which is influenced by how similar a stakeholder judges the source's values to be to their own, and confidence (trust in competence), which is influenced by past performance, both personal and via reports from others. People who trust a mining company or a government or an NGO are more likely to assess mistakes or poor performance generously, whereas those with lower social trust are more likely to judge the behavior much more harshly. Personal characteristics of message sources are emphasized, as is the establishment of shared values between communicators and receivers of messages (Karlin, 2012).

The challenge is that sustainable development itself is a matter of what people value (Shields and Šolar, 2002). This is clearly different across socioeconomic groups, cultures, and religions. The differences cannot be ignored. Human values are not fixed or independent of social, economic, and ecological context. As a result, there are multiple viewpoints on what sustainable development means, and how it should be achieved. Arguments about the role of mining in sustainable development reflect people's personal values across different countries, cultures, and circumstances (Shields and Šolar, 2005). Those values influence, and are influenced by the cultural, social, institutional, and economic framework within which that individual lives, and through that process become an ordered value set.

This is particularly true in the case of REEs mining projects due to the environmental and health issues that may be associated with the extraction of REEs. Figure 19 shows the flow of such influence (down) from values to impacts on systems and the flow (up) of information about how actions and impacts have, or have not, changed the status and functioning of social, economic and environmental systems (Shields, 2002).

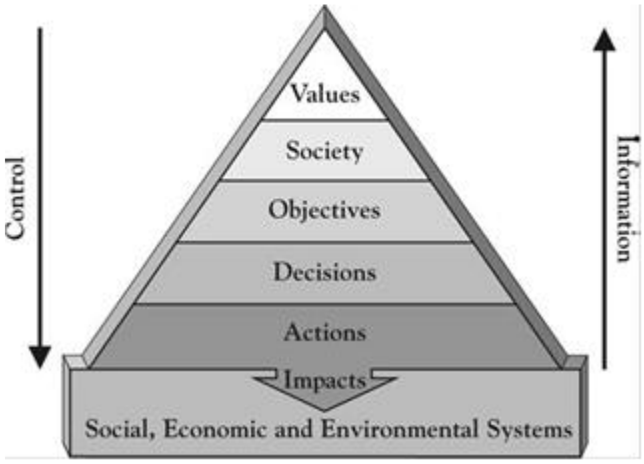

Figure 19 Control and information flow: hierarchical model of resource management (Shields, 2002)

For information to be effectively transmitted up through this hierarchical system so that it can influence both peoples' values and societal objectives with respect to SD and mining, it must be understandable and relevant. However, the process of transmitting information from one stakeholder (transmitter/sender) to another (receiver) is very complex.

The first problem is that people or stakeholder groups resist changes when they are exposed to new situations. People tend to listen to ideas that support what they already believe and do not hear what does not support what they believe, a phenomenon termed confirmation bias. This is even more applicable in the case of the extractive industries, which are facing a challenging business environment due to lost trust (MMSD, 2002). In some cases, actions that improve interests of one side could conceivably be harmful to the interests of a counter side (Martin et al., 1996). Individuals and groups that hold distinct philosophies, values, and interests, may be differentially affected by the implementation of given alternatives (Shields et al., 1999). In a recent study (Stacey and Stacey, 2014), on the perception of company board members on SD issues, it was argued that the executive leaders/board members/directors of mining companies are human beings subjected to related ambitions, emotions, and uncertainties. These human characteristics create barriers/obstacles to courageous leadership when it deals with issues related to the implementation of SD initiatives, including transparency and information sharing.

Secondly, during this process, information may be altered, introducing inaccuracies or misconceptions relative to the original message. Or the information may simply be presented incompletely or in a confusing manner. This may be more pronounced in cross-cultural situations where differences in language, ethics, and habits are an issue. In the worst case scenarios, intentionally misleading information, or no information at all, may be shared. Once the receiver stakeholder raises resistance to a message sent by the sender-stakeholder, the message becomes fuzzy and part of the information is lost. The resistance to the message may be so high that it sometimes turns into an impenetrable barrier (Kamenopoulos, 2008).

The main stakeholders in mining projects include the mining companies, and in most case the government representatives on one side, and the public (society) and NGOs on the other side. These two stakeholder groups continuously exchange information with each other before, during and post mining operations. Schematically the process that describes clear and fuzzy information flow during stakeholder communication is shown in Figure 20.

Fuzzy communication has significant negative implications for the acceptance of mining projects by stakeholders. If information is not clearly and transparently shared, the mining firm may be unable to gain a social license to operate, which refers to the level of acceptance or approval by local communities and stakeholders of mining companies and their operations. This is true regardless of the quality of the mining practices of the firm. The absence of the social license to operate increases the risks associated with the mining operation. This outcome is illustrated by the left-hand path of Figure 21. Conversely, effective communications, based on SD (C&I), when paired with sustainable mining practices (Botin, 2009; Rajaram et al., 2005; Richards, 2009), can eventually lead to the social license to operate. This more preferable outcome is illustrated on the right side of Figure 21.

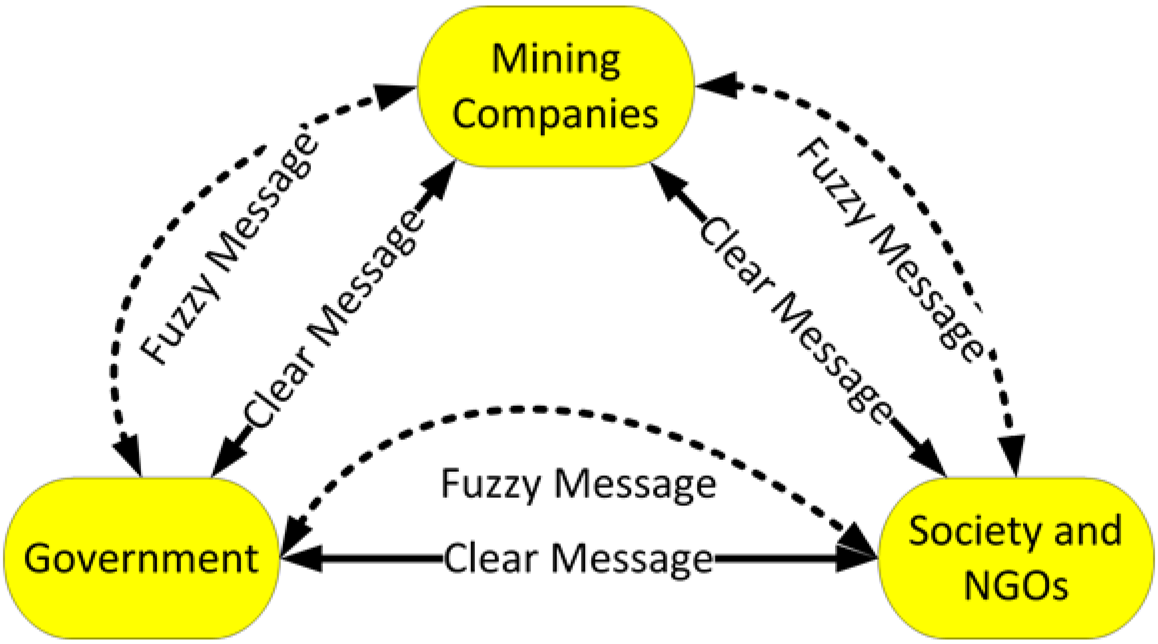

Figure 20 Clear and fuzzy information flow during stakeholder communication

The bonding material that ensures clear communication between stakeholders and mining companies can be mutually agreed upon between stakeholders based on a set of C&I of SD. These C&I would delineate a base line agreement on what information needs to be shared, which will reduce the friction and fuzziness between stakeholders and the firm. Indicators help people understand the complexities associated with mining and mineral resource management decisions, and can communicate the interconnectedness of physical and environmental systems and the inevitability of making tradeoffs among conflicting values, preferences and objectives (Shields and Šolar, 2005).

At the same time, a single piece of information or a set of SD indicators, can and will be interpreted in more than one way because stakeholders view indicator levels based on their own values and preferences. A measure that a company considers good might be considered unacceptable by a stakeholder and vice versa. And so, while it is certainly possible for a government or business to create and publish an “official” interpretation, doing so may be counterproductive if it undermines trust among stakeholders (Villas Bôas, et al., 2005).

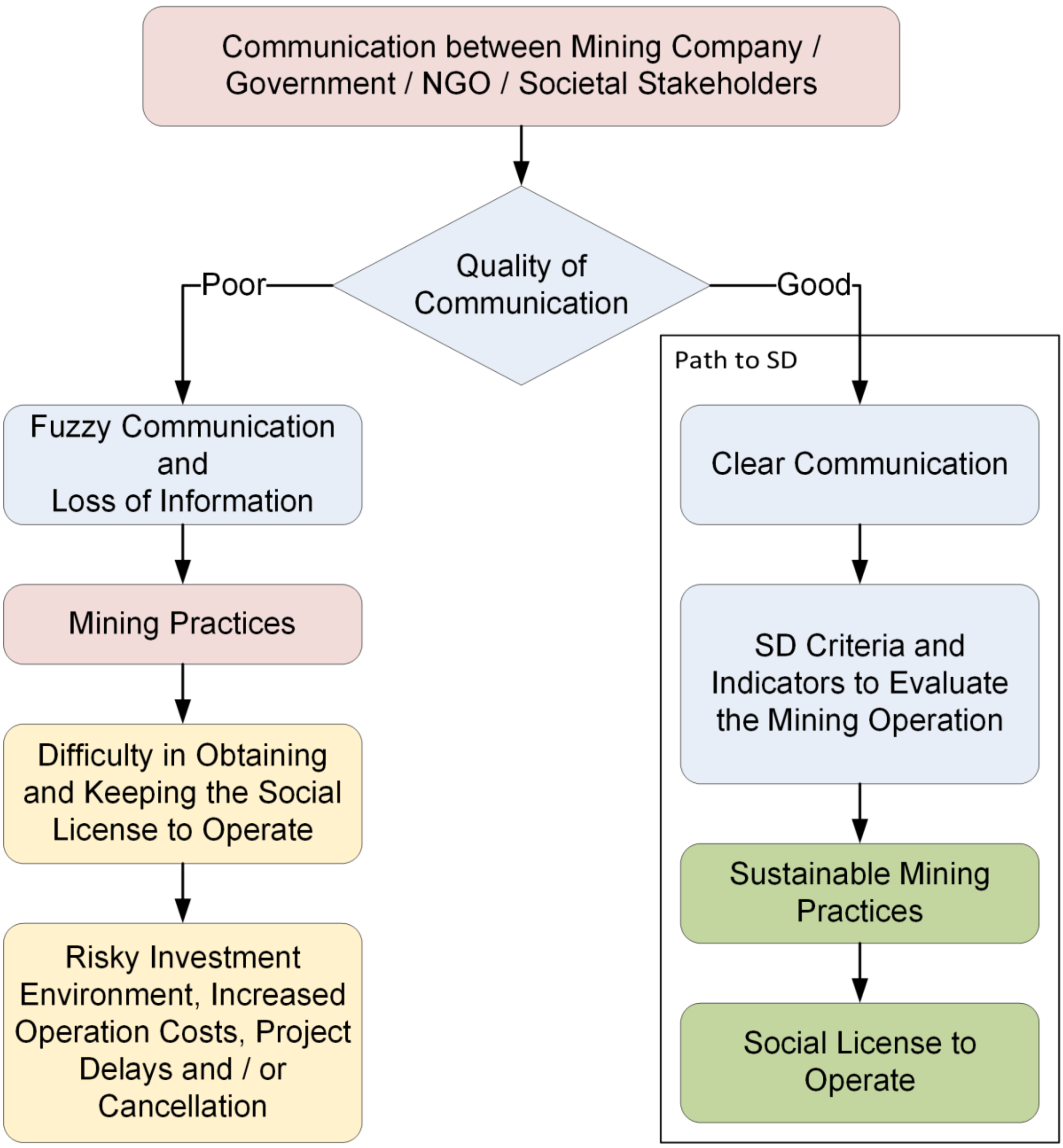

Figure 21 The process that promotes the sustainable mining of REEs

The establishment of a well-accepted set of indicators will increase the likelihood that mining will make a positive contribution to society, because factors that could negatively impact society, the economy and the environment will be tracked, problem identified, and hopefully solutions found and implemented. Factors that could have a positive impact would also be tracked, and possibilities for improvement of quality of life and well-being highlighted with the goal of ensuring that local/regional/country/international sustainability is enhanced during mining and the post-mining period. Of equal importance, regular and transparent reporting on indicators will increase the likelihood of firms gaining and retaining social license to operate.

7.3 Sustainable Development Criteria and Indicators for REEs Mining Projects

As Hilson and Basu (2003) point out, “The selection of indicators will undoubtedly vary on a case by case basis, but nevertheless involves the same process of identifying problems in need of evaluation using SDIs”. Moreover, as Perez and Sanchez (2009) point out, best reporting practices are always evolving, and stakeholder concepts of what information is needed evolve over time. Creating a supplementary set of C&I for REEs mining is consistent with this perspective. As discussed previously, the purpose of a particular set of criteria or indicators for the sustainable mining of REEs should be to deepen understanding and bridge the diverse perspectives of different stakeholders, and in so doing ease the resistance and lower the barriers to mineral development.

Consistent with the previous section, it is common to identify two main stakeholder groups in REEs mining. Mining companies and governments care about the REEs mining projects because of the need to provide resources to industry and to critical defense and the high tech sectors, and promote economic growth. On the other hand, NGOs and society care about potential environmental and social impacts of REEs mining projects. Because the concerns and motivations of these two groups with respect to REEs production and processing are very different conflicts may arise. For example, in 2012, the subject of a new REEs processing plant in Malaysia became the main issue of the national Malaysian elections (Kamenopoulos and Agioutantis, 2013).

In technical terms, mining of REEs is characterized by two basic attributes. The first attribute is the presence of thorium and/or uranium in many REEs-bearing ores. This attribute is directly linked to unwanted radioactivity. The International Atomic Energy Agency (IAEA) has published between 1996 and 2011 a distinctive number of reports in the IAEA Safety Series and the Safety Standards Series that are applicable in REEs mining projects. Examples of these reports include IAEA (1996), IAEA (2001), IAEA (2002) and IAEA (2011). The IAEA is also investigating the feasibility of using thorium as a replacement fuel for uranium in nuclear power generation suggesting that mining expressly to produce thorium is possible within the next decade (IAEA, 2005). Having C&I relevant to thorium extraction thus takes on additional importance.

Table 11 summarizes the particularities that differentiate REEs mining projects from most other mining projects. It was designed to incorporate the five pillars of the Sustainable Development framework for REEs mining projects: environment, economy, society, technology and geopolitics, and to incorporate the specific attributes that should be taken into consideration when selecting indicators for sustainable development of REEs mining projects, as discussed in more detail in Kamenopoulos et al. (2015b). Each particularity impacts every pillar to some degree. Taken on an individual basis most of these particularities apply to more than one mineral. For example, radiation is an issue in all uranium mining, diamonds are smuggled, coltan is mined illegally in the Democratic Republic of Congo, and media coverage impacts public attitudes about investment in many types of mines. REEs are unique in facing all these typical issues, while also having both strategic importance and a dominant government producer. Strategic is defined here to mean that the mineral is of high importance to the economy and for defense applications. China is the dominant producer and presently holds the entire world's refining capacity. They recently lost a case at the World Trade Organization brought against them by the United States and have said they will increase export quotas, but their virtual monopoly market power remains enormous (WTO, 2014).

Traditionally, sustainability related to mining and minerals has been considered at a single scale, either the mine site, or a national/regional scale (Shields and Šolar, 2005). However, as Table 11 makes clear, REEs mining has sustainability aspects that occur across multiple spatial scales. Their production and availability, or lack thereof, can impact the sustainability of an ecosystem, an industry, a local or regional economy, or a nation. All the foregoing differentiates the way that REEs mining projects should be treated from the sustainability point of view. Thus, there is a need to establish an additional set of indicators, tailor-made specifically for REEs mining projects, and that builds upon and supplements those indicators already available and spans the range of sustainability issues that need to be considered.

The particularities of REEs mining projects (Table 11) are linked to selected SD criteria and indicators as shown in Table 12. There is not, however, a one-to-one mapping from Table 11 cells to Table 12 C&I. This is because multiple indicators are needed to adequately describe the particularities. Also, it should be reiterated that these criteria and indicators are not intended for stand-alone use, but rather for use in addition to standard, widely used indicators, such as those from the GRI MMSS.

Table 12 is organized as follows. The 5 pillars are arrayed down the left side. Across the top of the table there are columns for criteria, rationale for inclusion, impact on sustainability (positive or negative), indicators, a related measure, and a proposed data source. Consider for example the probable presence of radiation, which is considered a particularity for REEs mining projects (Table 11). The rationale for inclusion is its danger to human health and it is addressed in Pillar 1 because it is an environmental issue (though it could be considered in Pillar 3 Society). There are two criteria: Radiation (public exposure) P1C2 and Radiation (occupational exposure) P1C3. The impact clearly is negative. Indicators are proposed, as are measures and a data source.

Taking into consideration the information provided in previous paragraphs a set of 31 sustainable development criteria and associated indicators for REEs mining projects were created (Table 12). Specifically:

- 3 C&I are related to the environment pillar
- 10 C&I are related to the economy pillar
- 9 C&I are related to the society pillar
- 4 C&I are related to the technology pillar
- 5 C&I are related to the geopolitics pillar

The indicators were developed to provide information that is not typically included in GRI-based sustainability reporting. They cover topics that influence stakeholders' opinions about the acceptability and importance of REEs mining at the local or regional/nation scales and in so doing will influence the firm's ability to gain/retain social license to operate.

Each criterion is linked to one of the particularity categories. The rationales presented for each C&I pair are intended to place them in a broader sustainability context, i.e., the achievement of the proposed UN Sustainable Development Goals (SDGs) (UN, 2014). The SDGs come into force upon the expiration of the UN Millennium Development Goals in 2015. The SDGs are aspirational in nature, but as a result they also incorporate many of the issues that stakeholders raise with respect to mineral development. The SDGs include, but are not limited to:

Goal 1. End poverty in all its forms everywhere.

Goal 2. End hunger, achieve food security and improved nutrition.

Goal 3. Ensure healthy lives and promote well-being for all at all ages.

Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all.

Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment.

Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable.

Goal 13. Take urgent action to combat climate change and its impacts.

Goal 16. Promote peaceful and inclusive societies for sustainable development.

Consider for example criterion P4C1: Availability of a Skilled Workforce. The rationale for its inclusion is: Hiring local residents is good for local economies and contributes to economic stability. This directly links to Goal 8. Communities are more likely to welcome mining operations that will contribute to sustainable economic development.

The impact descriptions reflect the potential positive or negative consequences of different indicator levels. In many cases only the positive or the negative impact is described, but there implicitly would be an opposite impact if the indicator level was higher or lower. For example, criterion P3C8: Income/Poverty. The positive impact statement is: Increasing incomes can increase support for mining if the two can be linked, and decrease the likelihood of illegal mining and smuggling. Clearly decreasing incomes would have the opposite effect. Also this C&I pair links to SDG 1. REEs mining that is likely to reduce poverty in the area adjacent to the mine is more likely to be welcomed than mining that has no local economic benefits. More generally, stakeholders are concerned, explicitly or implicitly, about the balance and distribution of the costs and benefits of REEs mining and these C&I pairs can assist them in assessing the relationship between the two.

The impact of a REEs mining project in a specific area may be overall positive or negative. The conclusion reached depends on the perspective of the stakeholder and the different pillars/criteria employed, as well as the different weights or levels of importance assigned to each C&I for conditions before, during and after project completion. For example, if the indicator related to toxic waste emissions (P1C1) is higher during and post mining, this will be considered as a negative impact for all stakeholders. Alternatively, if the indicator related to Political Stability and security of the country (P5C1) increases during and post mining compared to the level before, this will be considered a positive impact. If one of these is weighted as more important than the other, then their inclusion in the analysis will push the estimate of overall impact in either a more negative or more positive direction. Clearly, open dialogue about the meaning of the combined GRI-based and supplementary REEs indicator reporting will be needed if consensus is to be reached and conflict avoided.

Table 11 Particularities of REEs mining projects

Differentiation Particularities	Pillars Environment	Economy	Society	Technology	Geopolitics
Presence of radiation	• Negative impact for a long period of time • Need for legal framework and strict governmental policies	• Negative impact at local / regional / country level	• May create turmoil within local / country level	• Need for use of advanced technologies to control	• May create conflicts with neighbor states
Market	• High demand of REEs-based end products leads to further increase of REEs projects increasing chances for environmental damage. • REEs-based end products in green energy assist to the reduction of CO2.	• Extremely high global added value from mine to market • High control of supply side from China • REEs are not traded in market or metal exchanges • Potential to negatively impact local economy due to contamination or increased use of infrastructure.	• REEs cover the needs of global society such as mobile phones, green energy, etc.	• Creates demand for engineering advancements and qualified workforce.	• May create conflicts and trade wars between different countries
Smuggling	• Deficient environmental mining processes	• Black market • No transparency	• Unsafe/unhealthy working conditions • Corruption	• Unknown quality of products sold	• Conflict risks • Corruption
Illegal mining	• Deficient environmental mining processes	• Black market • No transparency	• Corruption	• Unknown quality of products sold	• Conflict risks • Corruption

	Pillars				
Differentiation Particularities	Environment	Economy	Society	Technology	Geopolitics
Media	• Media negative role: distribution of bad news due to a probable mishap and / or environmental impacts • Media positive role: optimistic information provided to public regarding the necessity, importance and linkage of REEs to green economy and to the stoppage of climate change.	• Media positive role: optimistic information provided to public regarding the necessity, importance and linkage of REEs to the development of economy at local/regional/global level.	• Media negative role: distribution of bad news due to a probable occupational mishap and/or unsafe/unhealthy working conditions. • Media positive role: optimistic information provided to public regarding the necessity, importance and linkage of REEs to green economy and to the stoppage of climate change.	• Media positive role: optimistic information provided to public regarding the necessity, importance and linkage of REEs to the development of high tech products	Media negative role: distribution of bad news due to a probable conflicts at local/regional/global level
China's dominance in REEs mining and refining	• Deficient environmental mining processes	• Major economy risks that China will dominate in the global high tech sector	• Unsafe/unhealthy working conditions	• Major technology risks that China will dominate in the global high tech sector (from clean energy to defense / space industries)	• Major geopolitical risks that China will dominate in the global high tech sector (from clean energy to defense / space industries)

Table 12 Criteria and Indicators for the Sustainable Development of REEs mining projects

Pillars	Criteria	Rational	Impact		Indicators	Metric	Indicative sources
	Particularity		Positive	Negative			
Pillar 1 Environment	P1C1: Toxic contamination (Smuggling, Illegal Mining, Media)	Significant historical evidence of contamination near mining sites, e.g., in U.S. and China.		Degradation of human health and ecosystems.	1. Emissions of heavy metals at the specific REEs mining site and the surrounding public area. OR 2. Concentration of heavy metals in rivers/lakes and soil at the specific REEs mining site and the surrounding public area.	Emissions/ concentration of: Barium, beryllium, copper, lead, manganese, zinc, sulfide minerals, carbonate minerals, fluorine and asbestos minerals	Data shall be measured utilizing company's own sources
	P1C2: Radiation (Public Exposure) (Presence of Radiation, Media)	Radiation is dangerous.		Degradation of human health.	Radiation doses to the public are required not to exceed an effective dose of 1mSv in a year; or under special circumstances, an effective dose of up to 5 mSV in a single year provided that the average dose over five consecutive years does not exceed 1 mSv per year. Related to the specific REEs mining project.	mSv per year	Data shall be measured utilizing company's own sources.
	P1C3: Radiation (Occupational Exposure). (Presence of radiation, Media).	Radiation is dangerous		Degradation of human health	The occupational exposure of any worker shall be controlled that the following limits be not exceeded: (a) an effective dose of 29 mSv per year	mSv per year	Data shall be measured utilizing company's own sources.

Pillars	Criteria	Rational	Impact		Indicators	Metric	Indicative sources
Pillar 1 Environment					averaged over five consecutive years; (b) an effective dose of 50 mSv in any single year; (c) an equivalent dose to the lens of the eye of 150 mSv in a year; and (d) an equivalent dose to the extremities (hands and feet) or the skin of 500 mSv in a year. Related to the specific REEs mining project.		
Pillar 2: Economy	P2C1 Resource rent (Market, illegal Mining, Smuggling, Media)	REEs production and sales generate resource rent that can be retained as profit, paid to government as taxes or royalties, or reinvested in the local community.	Resource rent provides revenue to government, and can be invested locally in roads, schools, etc.	Presence of high resource rents is an incentive for illegal mining and smuggling.	Tax and royalty rate, and % returned to local communities.	Rate and %	Government regulations.
	P2C2: Agriculture (Market, Media)	Historical evidence of toxic contamination of water and soil.		If the local economy is highly dependent on agricultural production the presence of a REEs mining site near the area may decrease the	Proportion of local GDP based on agriculture.	%	Data shall be obtained/retrieved from national statistical sources or measured utilizing company's own sources

Pillars	Criteria	Rational	Impact		Indicators	Metric	Indicative sources
Pillar 2: Economy				local GDP if products are perceived to be contaminated.			
	P2C3: Industrial Development (Market, Media)	Mining sites are industrial developments with infrastructure and utilities installed. .	Post-mining brownfield redevelopment can benefit local economies.		Presence/absence of post-mining development plan. .	%	Data shall be mine plan.
	P2C4: Tourism (Market, Media)	Presence of mining can influence people's willingness to visit an area.	Mining project provides benefits to residents. Mining area becomes touristic attraction at post mining period.	Mining project creates costs to residents: less tourists visit the area.	Ratio of local residents to tourists in major tourist regions and destinations near to the specific REEs specific mining project.	Number of local residents divided to number of tourists visiting the area per year (ratio).	Data shall be obtained/retrieved from national statistical sources or measured utilizing company's own sources
	P2C5: Settlements (Market, Media)	If new mining projects bring in new residents during construction and operation phases, the availability of housing can be impacted.	Mining project provides benefits to residents. The specific REEs mining project contributes to the improvement of housing settlements.	Mining project creates costs to residents: availability of housing decreases as miners move into area.	Percentage of vacant housing related to the specific REEs mining project.	%	Data shall be obtained/retrieved from national statistical sources or measured utilizing company's own sources
	P2C6: Infrastructure and Transport (Market, Media)	Increased industrial development in an area also increases use of road and demands on infrastructure.		Mining project creates costs to residents: increased use degrades roads.	Level of transportation. Related to the specific REEs specific mining project.	km of railroads and/or tarmac roads, change in road usage	Data shall be obtained/retrieved from national/international statistical sources or

Pillars	Criteria	Rational	Impact		Indicators	Metric	Indicative sources
Pillar 2: Economy							measured utilizing company's own sources
	P2C7: Economic diversity (Market, Media)	Communities are more resilient if their economies are diverse.	Re-investment of resource rent in local economy can increase economic diversity.	Sometimes mineral development results in a decrease in non-mining economic diversity.	Level of economic diversity.	Statistic	Data shall be obtained/retrieved from national statistical sources.
	P2C8: Entrepreneurship I (Markets)	Entrepreneurship is a feature of resilient economies.	Business creation is positive for local economies.		Number of business permits issues by local authorities.	Number.	Local data collection.
	P2C9: Entrepreneurship II (Markets)	Entrepreneurship is a feature of resilient economies.	Influx of engineers and technical specialists to the mining area can catalyze high tech entre-preneurship.		Number of business permits for high tech businesses issued by local authorities.	Number	Local data collection.
	P2C10: Access to energy	New industrial development can impact existing energy distribution systems.	To support new mine, energy infrastructure is upgraded.	As a result of new mine, less energy is available to the surrounding area.	Accessibility to sufficient energy at the specific REEs mining site. Contributing to or decreasing the availability of energy to adjacent communities	%	Data shall be obtained/retrieved from national/international statistical sources or measured utilizing company's own sources
	P3C1:	Introduction of new	Maintenance of	Negative	Existence of community	Change in total	Data shall be

Pillars	Criteria	Rational	Impact		Indicators	Metric	Indicative sources
Pillar 3: Society	Community life (Media)	industrial development can impact community life.	community institutions adds to community resilience.	impacts increase opposition to mining.	institutions at the area near the specific REEs mining site (churches, trade-unions, community centers, museums, schools etc.)	number of institutions per square Km	obtained/ retrieved from national statistical sources or measured utilizing company's own sources.
	P3C2: Health and population (Presence of radiation, Media)	Healthly workers and community members are essential for resilient, stable communities.		Increasing rates of illness and injury increase opposition to mining if the two can be linked.	Life expectancy at birth at the area near the specific REEs mining site.	Years	https://www.cia.gov/library/publications/the-world-factbook/rankorder/2102rank.html http://www.census.gov/compendia/statab/2012/tables/12s1339.pdf
	P3C3: People's happiness and well-being (Media)	Happiness at the area near the specific REEs mining site is an aspiration of every human being, and can also be a measure of social progress and well-being.		Decreasing levels of happiness and well-being decrease support for mining if the two can be linked.	Utilize UN method of estimating subjective happiness. http://unsdsn.org/resources/publications/world-happiness-report-2013/ http://unsdsn.org/files/2013/09/WorldHappinessReport2013_online.pdf	Rating/ranking	Local data collection.
	P3C4: Human	The Human Development Index	Higher HDI is better and will		HDI: the geometric mean of normalized indices for	Rating/ranking	http://hdr.undp.org/en/sta

Pillars	Criteria	Rational	Impact	Indicators	Metric	Indicative sources
Pillar 3: Society	development (Media)	(HDI) is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living.	increase support for mining if two can be linked.	each of the three dimensions. It concerns the country of the specific REEs mining project.		tistics/hdi
	P3C5: Human rights (Media)	Human rights are rights inherent to all human beings, whatever our nationality, place of residence, sex, national or ethnic origin, color, religion, language, or any other status. We are all equally entitled to our human rights without discrimination. These rights are all interrelated, interdependent and indivisible.	Increasing quality of human rights can increase support for mining if the two can be linked.	Calculation of the countries' Human Rights Rank Indicators (as a percentage). It concerns the country of the specific REEs mining project.	Rating/ranking	http://www.ihrri.com/contry.php
	P3C6: Family Life (Media)	Introduction of a new industrial activity in an area can impact families.	Increasing quality of family life can increase support for mining if the two can be	Change in divorce rate and instances of domestic violence and child abuse at the area near the specific REEs mining site may create societal	Number of divorces and incidents per 1,000 population	

Pillars	Criteria	Rational	Impact	Indicators	Metric	Indicative sources
Pillar 3: Society			linked.	problems.		
	P3C7: Access of local people/society to vital resources: food/water security. (Illegal mining, Smuggling, Media)	Access to affordable, nutritious and healthy food and clean water may prevent resource wars (conflicts) at local/regional/country/inter-national level.	Increasing access to food and water and water increase support for mining if the two can be linked, and decrease the likelihood of civil unrest.	Percentage of population without access to adequate food or water.. It concerns the communities near the specific REEs mining project.	%	Data shall be obtained/retrieved from national/international statistical sources
	P3C8: Income/poverty (Illegal mining, Smuggling)	Reduced poverty levels may prevent conflicts/ immigration at local/regional/ national/ international levels.	Increasing incomes can increase support for mining if the two can be linked, and decrease the likelihood of illegal mining and smuggling..	Proportion of population living near the specific REEs mining project that is below national poverty line.	%	Local data collection.
	P3C9: Activism (Media)	Pro- and anti-mining activity influences government permitting to mine and social license to operate.	Reports critical of mining operations can decrease support for mining.	Presence of pro- and anti-mining groups locals, nationally, internationally advocating regarding the REEs mining project. Number of media reports for and against the REEs mining project.	Statistics	Local data collection.
Pillar 4: Technology	P4C1: Availability of skilled work -force (Market)	Hiring local residents is good for local economies and contributes to economic stability.	Providing employment to local residents increases support for mining.	Education levels in the workforce or the population at the area near the specific REEs mining site.	1. Percentage of population with post-secondary qualification 2. Percentage of people with	Data shall be obtained/retrieved from national statistical sources or measured

Pillars	Criteria	Rational	Impact		Indicators	Metric	Indicative sources
Pillar 4: Technology						secondary qualification.	utilizing company's own sources
	P4C2: Innovation I (Market)	Technological innovation benefits society.	Investment in industry and academia increases likelihood of technological innovations.		Investment in high tech industries or academic institutions. It concerns the country or area near the specific REEs mining project.	%	Data shall be obtained/retrieved from national statistical sources.
	P4C3: Innovation II (Markets)	Technological innovation benefits society.	Innovation leads to new technologies for use in mining, refining and reclamation.		Technological innovation as measured by patents. It concerns the country of the specific REEs mining project.	Number of patents	Data shall be obtained/retrieved from national statistical sources
	P4C4: Innovation III	Technological innovation benefits society.	Innovation is more likely to take place when higher numbers of people are employed technical fields related to mining.		Employment in Tech-knowledge intensive activities as a percentage of total employment. It concerns the country or area near the specific REEs mining project.	%	Data shall be obtained/retrieved from national statistical sources
Pillar 5: Geopolitics'	P5C1: Political stability and security of the country (Markets)	Stability of supply for an essential commodity**.**	Increased political stability will increase stability of supply.	Decreased political stability will Decrease stability of supply.	Political stability and security ratings. It concerns the country or area near the specific REEs mining project.	Rating/Rank	www.govindicators.org
	P5C2: Global security of REEs supply. (Chinese	Stability of supply for an essential commodity.	Decreased monopoly power by one producer decreases likelihood of	Increased monopoly power by one producer increases	Impact of REEs mining project to global supply of REEs.	Percentage change in Chinese monopoly in global REEs production	Data shall be obtained/retrieved from international statistical

Pillars	Criteria	Rational	Impact		Indicators	Metric	Indicative sources
Pillar 5: Geopolitics'	dominance)		anti-competitive actions or embargoes.	likelihood of anti-competitive actions or embargoes.			sources
	P5C3: Quality of democracy I: Transparency (Illegal mining, Smuggling)	Power concentration to small groups (oligarchy). Transparency contributes to equal distribution of wealth within the society's members and to the minimization of corruption. Transparency may prevent creation of oligarchic groups at local / regional / national / international level. It concerns the country of the specific REEs mining project.	Transparency is a dis- incentive for illegal mining and smuggling.		Level of transparency	Rating/ranking	http://www.transparency.org/
	P5C4: Quality of democracy II: Fragile/failed state (Illegal mining, Smuggling)	Fragile/failed states have less control over industrial activities.		Fragile/failed status makes illegal mining and smuggling of commodities is more likely.	Fragile/failed state index. It concerns the country of the specific REEs mining project.	Rating/ranking	http://ffp.statesindex.org/

Pillars	Criteria	Rational	Impact	Indicators	Metric	Indicative sources
	P5C5: Quality of democracy III: governance (Illegal mining, Smuggling)	High quality governance improves democracy and reduces the country risk.	Poor quality of governance makes illegal mining and smuggling more likely.	The Worldwide Governance Indicators (WGI) are a research dataset summarizing the views on the quality of governance provided by a large number of enterprise, citizen and expert survey respondents in industrial and developing countries. .	Rating/ranking	http://info.worldbank.org/governance/wgi/index.aspx#home

Chapter 8. A new Hybrid Decision Support Tool for evaluating the sustainability of mining projects

The 2030 Agenda for Sustainable Development of the United Nations set out 17 Sustainable Development Goals (SDG) with 169 associated targets. This Agenda is a plan of action for people, prosperity and the planet. All countries and all stakeholders, acting in collaborative partnership, should consider implementing this Agenda. These SDGs and targets will stimulate action over the next 15 years in areas of critical importance for humanity. Quality, accessible, timely and reliable disaggregated data will be needed to help with the measurement of the progress. In accordance to the UN 2030 Agenda, such data is considered a key to decision making for SD. The Agenda called upon all private business, from micro-enterprises to cooperatives and multinationals, to apply their creativity and innovation to solving sustainable development challenges (UN, 2015).

In addition to these challenges the extractive industry may be confronted by the unwanted effects of environmental policy mechanisms (Gabaldon-Estefan et al., 2016), energy efficiency issues related to specific operational processes such as loading and hauling (Awuah Offei, 2016) or the environmental effects caused directly by the excavation process (Castilla-Gomez and Herrera-Herbert, 2015), and low carbon issues associated with production, supply chain and operations management perspectives (Santibanez-Gonzalez et al, 2016). As a result, decision making is becoming a complex process that should utilize logic and inclusive reasoning to make informed decisions based on available information. Decision making is not a straightforward procedure; the right decisions and selection of optimal alternatives are not easy and demand time (Kostovic and Gligoric, 2015). When applied to SD, this vital process involves evaluation of a number of outcomes within a social, economic and environmental framework, although many times balancing social, economic, and environmental costs and benefits can be a subjective process (UN, 1987). In any case, such assessments should eventually promote responsible and sustainable development - a core aim of many international policies (Gonzalez et al., 2013).

Furthermore, the “Social License to Operate” has become an important prerequisite for the extractive industries, since it helps minimizing the business risks related to probable social unrest or opposition stemming from the realization of mining projects. Research has shown that in order to achieve a more socially sustainable mining industry where social conflict around mining operations is minimized and the public is able to experience the benefits of resource development, both the mining industry and governments need to review their methods of engaging with citizens to build trust in those stakeholder relationships (Zhang et al. 2015). Society is today sensitive in the case of environmental protection, transparency and means of communication and has adopted a general pro-environmental behavior; this may cover a wide range of initiatives spanning from large mining projects to personal consuming habits. Furthermore, consumers require information that will help them judge the value of environmentally conscious products by themselves and put more emphasis on the transparency of label certification results than the involvement of experts (Kikuchi-Uehara et al., 2016).

The tools that can potentially contribute to the assessment of SD and support decision making have been divided into three main categories: i) indicators and indices, ii) product related assessment, and iii) integrated assessment (Ness et al., 2007). Typically, such indicators can be non-integrated (e.g., environmental pressure indicators), regional flow indicators (e.g., based on an input/output analysis) or integrated indicators (e.g., representative of a well-being index). The second category includes product related tools that focus on flows in connection with production and consumption of goods and services. Finally, the third category of tools is used for supporting decisions related to a policy or a project in a specific region. A decision support system (DSS) is defined as a software based tool assisting in the decision-making process by interacting with both internal and external users and databases, while utilizing standardized or specific algorithms for problem solving (Burstein and Holsapple, 2008 as discussed by Mattiussi et al., 2014). Multi-criteria decision-making (MCDM) "*deals with a general class of problems that involves multiple attributes, objectives and goals*" (Zeleny, 1982 as discussed by Mattiussi et al., 2014).

This chapter proposes a new hybrid DSS tool which is based on an integrated indicators-based SD assessment process for supporting decision making in mining projects. The developed DSS tool combines baseline indicators, i.e., evaluated before starting up a project, and indicators evaluated during project implementation and after project completion. The tool considers local, regional, country, and international conditions during these three distinct time frames. For example, project stakeholders can compare the economic activity in an area before starting up a project to the economic levels achieved during project implementation as well as after the project has been completed. Thus, any advantages and disadvantages with respect to SD principles can be easily outlined. In addition, this work integrates the proposed DSS with the Sustainable Development Framework presented and discussed in previous works (Kamenopoulos et al., 2015a; 2015b).

This chapter is organized as follows: The background section reviews and discusses different DSSs that have been proposed in a Sustainable Development context as applied to the energy sector, the extractive industries and some industrial systems that have an environmental component; sustainable manufacturing, which is an emerging discipline, is not discussed here. Subsequently, the developed DSS model, which incorporates different SD indicators as applied to mining projects with respect to Sustainable Development challenges and opportunities, is presented. The proposed system, named “ACROPOLIS DSS”, can be used to assist involved stakeholders in critical decisions, especially when issues such as stakeholder participation, transparency and trade-offs are addressed. The proposed DSS is based on Multi-Criteria Decision Analysis (MCDA) combined with Multi-Attribute Utility Theory (MAUT). Multi-criteria decision analysis (MCDA) methods have been developed to support decision makers in their unique and personal decision process; MCDA is a discipline of operations research that encompasses mathematics, management, informatics, psychology, social science and economics (Ishizaka and Nemery, 2013). Multi-Attribute Utility Theory (MAUT) is based on the main hypothesis that every decision maker tries to optimize, consciously or implicitly, a function which aggregates all their points of view (Ishizaka and Nemery, 2013). In MAUT the decision maker’s preferences can be represented by a function, called the utility function (Keeney and Raiffa, 1976). This function is not necessarily known at the beginning of the decision process, so the decision maker needs to construct it first.

8.1 Background

The concept of applying a DSS with respect to SD principles in technical projects is not new. In this section, several such systems are evaluated as published in the international literature. However, none of these systems has been directly applied to mining projects.

Two such models, which address stakeholder input, have been recently proposed. The first one developed a DSS based on MCDA to promote community involvement in the case of mining projects (Erzurumlu and Erzurumlu, 2015). The MCDA which was used to assess the most relevant factors for stakeholder strategy evaluation includes perspectives upon which new alternatives might be developed, and assesses these alternatives based on multiple economic and social criteria. The preference function assigned to each criterion illustrates how each stakeholder changes his/her preference with the difference in performance level for two alternatives. A multi-criteria preference index was created by the weighted average of the corresponding preference functions for each criterion utilizing the weighting factors assigned previously by each stakeholder to every criterion. Although the model is based on the three SD pillars (social, economic, environmental) it is only focused on the preliminary stage of mining projects and does not cover the mining stage during mining and the stage following the completion of a mining project. The model follows the "people-first" approach to support the involvement of local communities before a mining project is initiated and especially at the design stage. Also, the model does not intend to incorporate the criteria and indicators utilized into the broader SD policy context i.e., the achievement of the United Nations SDGs as they were stated at the UN 2030 Agenda for Sustainable Development (UN, 2015).

The second model was proposed by Poplawska et al. (2015) who created a DSS utilizing fuzzy logic in order to assess and categorize stakeholders involved in an SD process in a set of groups. In order to categorize the stakeholders in groups, their importance was evaluated by indicating the exact degree of membership to a particular interest group. The fuzzy set theory allows intermediate degrees of membership between elements in a given set. Membership is defined based on criteria which are selected from a list of attributes and is assessed by the decision maker. Thus by calculating fuzzy scores for every stakeholder, the model provides the ranking of stakeholders. The authors utilized this DSS in order to construct the profile of key extractive sector stakeholders and measure their salience in a corporate social responsibility context.

Similar systems that have been fully or partially applied to the extractive industries include a DSS model developed by Hunt et al. (2013) which was based on MCDA and combines two other tools: a decision rationale and a probabilistic forecasting tool. The DSS was applied to the energy sector in order to determine the recommended sources of electricity generation in different locations in the United Kingdom, paying attention to water consumption and water purification using hybrid power and desalination plants. For the MCDA tool the Weighted Sum Model was utilized based on Fishburn (1967). The Decision Rational tool was based on the methodology of Issue Based Information Systems (IBIS). For the probabilistic part of the DSS a time series methodology involving the Mean Absolute Deviation (the average difference between the data and the forecast) in order to create a range of predicted values and their probabilities were used. This was done because the researchers claimed that decision taken today may not be the recommended decision in a month's time, and the ability to anticipate changes or analyze risks is a key to empowering people to make better decisions in the future.

Mattiussi et al. (2014) created an energy supply DSS for sustainable plant design and production. The authors used multi-objective and multi-attribute decision-making modeling together with impact assessment of the emission outputs. The proposed model consisted of three major decision-making steps: a) problem classification/definition, b) alternative generation/evaluation, and c) alternatives negotiation/selection and action determination. In the first step the Environmental Impact Assessment was used in order to evaluate the total EIP emissions' inventory and impacts. In the second step, a multi-objective mathematical model, including economic and environmental objectives in a Pareto-frontier, was utilized to evaluate different scenarios of combined heating and power plants (internal combustion engine, gas turbine, micro-turbines and fuel cells) and two types of photovoltaic plants. In the third step, the model utilized a multi-attribute method (Analytic Hierarchy Process) for selecting the best alternative among the Pareto-frontier efficient solutions. The model was applied to a case study of an Eco-Industrial Park located in Perth, Western Australia.

Paraskevas et al. (2015) developed an environmental assessment tool aiming to support decision making related to the sustainable management of metal resources during secondary aluminum production. This tool aimed to the minimization of material down-cycling and maximization of the scrap usage. The DSS was based on Life Cycle Assessment tool as this is described by ISO (2006). The DSS aimed to facilitate environmental impact calculations, express material, dilution and quality losses during aluminum recycling in LCA studies, and determine, from an environmental point of view, the optimal metal inputs for the aluminum recycling process. The model considered the composition of the metal inputs and the desired target aluminum specifications and also took into account the material input/output interconnections focusing on the contamination of the scrap streams by the residuals that pose a great challenge in aluminum recycling.

Ruiz et al. (2012) developed a spatial DSS based on a Geographic Information System (GIS) platform for planning sustainable industrial areas. The system was applied to a district of 646.2 km^2 located in Cantabria (Northern Spain). The model was based on the previous work of Fernandez and Ruiz (2009) which included more than two hundred SD variables. The new model used fewer variables (75) that were selected through various meetings and group discussions with the stakeholders involved. First, the evaluation and selection of suitable geographical areas was conducted. Then, the defined variables were evaluated according to criteria and reference values using Fuzzy Logic functions that normalize the results between 0 and 1. The weighting factors of the criteria were obtained using the Analytical Hierarchy Process. The GIS platform allowed the development of digital maps for existing areas that can be evaluated and the different zones that can be distinguished according to their suitability for the location of potential industrial areas.

Table 13 presents a summary of the above mentioned models.

Table 13 Description of DSS models

Reference	Method	Applied Techniques	Sector
Hunt et al. (2013)	MCDA	Weighted Sum Model	Energy
Poplawska et al. (2015)	Optimization	Fuzzy Logic – Weighted Sum Model	Extraction industry
Erzurumlu and Erzurumlu (2015)	MCDA	Preference Ranking Organization	Extraction industry
Ruiz et al. (2012)	MCDA	Fuzzy Logic – Analytical Hierarchy Process – GIS platform	Planning & Design
Mattiussi et al. (2014)	Optimization	Multi-objective multi-attribute mathematical model - Analytical Hierarchy Process	Planning & Design
Paraskevas et al. (2015)	LCA	Mathematical programming	Sustainable manufacturing

Despite the aforementioned research efforts into the SD-DSS field, to the best of our knowledge, there is currently a lack of a complete DSS framework, tool or method that can be used to approach the sustainability concepts in a holistic manner as these have been described and recommended by the UN 2030 Agenda for Sustainable Development (UN, 2015).

To fulfil this gap, this dissertation proposes a state-of-the-art DSS which allows decision makers to evaluate multiple options that may offer alternate solutions in "GO-NO-GO" situations. The proposed DSS is based on the MCDM theory and is dynamic in that it allows flexibility and changes to the levels of decision makers and stakeholders depending on the field/project that it will be applied.

8.2 Methodology

As already mentioned, the "ACROPOLIS DSS" presented in this dissertation is based on a MCDA and on the MAUT. The DSS was constructed in the Microsoft Excel™ 2013 environment and its core is based on criteria and indicators in order to assist decision makers/stakeholders to better assess the impact of a mining project from the sustainability point of view. The proposed DSS was then integrated into a state-of-the art Sustainable Development Framework (SDF) (Figure 14) which was previously developed by Kamenopoulos et al., (2015b).

In summary, the recommended SDF includes five SD pillars (economy, society, environment, technology and geopolitics), three controlling/limiting factors (policy, governance and stakeholders), and a number of output quantities (indicators) to be used in decision making. Using the recommended SDF facilitates addressing the unique and specific challenges present in mining projects (Giurco and Cooper, 2012; Fonseca et al. 2013; Corder, 2015; Kamenopoulos et al., 2015b).

Sustainability assessment from the point of view of multi-criteria analysis has the following characteristics: multiple stakeholders, with distinctive objectives and preferences; a decision context of quantitative and qualitative aspects; and multiple alternatives with different positive or negative impacts accruing to different stakeholders (Kamenopoulos et al. 2015a; 2015b). From the SD point of view, some of the main questions that the decision makers may face when working with project evaluation include the following are:

- What are the appropriate processes to be used in order to assess the project?
- What are the criteria that should be used and what are their corresponding weighting factors?
- Which process should be used to allow different stakeholders to trade-off, negotiate or bargain?
- Is this process clear and transparent?
- Should a nominated project be completely rejected or can it be re-considered or even approved under a number of modifications? Which are these modifications?
- Should any specific level of index/indicators for approval or rejection be established?
- How sensitive should the final solution be to specific stakeholder preferences?
- Are there provisions that can be implemented to continuously monitor the project throughout its life cycle (before, during and after the project) in a reliable manner?
- How should the assessment of multiple projects be handled?

The MCDA is a technique which supports decision makers when they need to compare different alternatives and decide which one should be selected. The MCDA is diachronically used in many different fields and sectors including sustainable development (Siskos and Hubert, 1983; Zopounidis, et al., 1995; Haralambopoulos and Polatidis, 2003; Omann, 2004; Sullivan, 2012). The MCDA incorporates mathematics, management, informatics, psychology, social science and economics (Ishizaka and Nemery, 2013). One of the basic attributes of the MCDA is the participation of stakeholders at the decision making through the negotiation process (trade-offs) (Mullen, 2004). This attribute has made the MCDA a very attractive analytical tool to support decision making processes. In addition, the MCDA integrates unique and personal decision making practices of individual decision makers (Ishizaka and Nemery, 2013).

The MAUT was created by Keeney and Raiffa (1976). In the MAUT the preferences of the decision makers are expressed by a utility function which expresses the level of preference that a decision maker has on a set of alternatives. The alternatives are compared under specific criteria (attributes). Every criterion has its own weighting factor. The most common MAUT method is the additive model which is represented by the following equation (Ishizaka and Nemery, 2013):

$$V_j = \sum w_i p_{ij} \qquad (1)$$

where:

V_j is the aggregate score of the j^{th} alternative,

p_{ij} is the score of the j^{th} on the i^{th} criterion, and

w_i is the weighting factor of i^{th} criterion

A basic constraint of MAUT dictates that the sum of all criteria weighting factors should be equal to one as shown by equation (2):

$$\sum w_i = 1 \qquad (2)$$

The relevant importance of each criterion is expressed by its own weighting factors under the preference of the decision makers. The Simple Multi-Attribute Rating Technique (SMART) is a technique which calculates the criteria weighting factors; the technique was developed in 1977 (Edwards, 1977) and improved in 1994 (Edwards and Barron 1994). SMART calculates the weighting factors in two phases: during the first phase, the decision-makers are asked to rank the criteria according to their own preferences from the most to the least important. In the second phase, a number of points (typically 10), is allocated to the least important criterion. Subsequently, 10 additional points (i.e., a total of 20 points) are allocated to the second least important criterion and so forth until all criteria have been allocated with points accordingly. To normalize the total score and comply with the constraint of equation (2), the points allocated to each criterion are divided by the total number of allocated points (Sullivan, 2012).

In the case of the recommended SDF the selection of criteria and indicators was based on available literature (IISD, 2002; Valta et al., 2007; Tzeferis et al., 2013; Zhang, 2014; World Bank, 2014; Kamenopoulos et al., 2015a) taking into consideration the particularities of specific projects.

Weighting factors are assigned not only to the criteria but to the Sustainable Development pillars as well. This is due to the fact that each SD pillar may have a different relative importance for each stakeholder. The SMART technique was modified for the calculation of the weighting factors: initially, the weighting factors of SD pillars, and then, the weightings of the criteria (indicators) were calculated. Equations (1) and (2) were modified as shown below (equations 3, 4, and 5) to fully correspond to the additional weighting factor calculations:

$$V_j = \sum b_k w_i \, p_{ij} \qquad (3)$$

where:

V_j is the aggregate score of the j^{th} alternative,

p_{ij} is the score of the j^{th} on the i^{th} criterion, and

w_i is the weighting factor of i^{th} criterion

b_k is the weighting factor of k^{th} pillar

The constraints are:

$$\sum w_i = 1 \qquad (4)$$

$$\sum b_k = 1 \qquad (5)$$

Actually, parameter V_j represents the total score of sustainable paths for the mining project. Thus, the total scores of four sustainable paths were calculated:

√ The total score of the ideal sustainable path (SPI).

√ The total score of the sustainable path before project start (SPB).

√ The total score of sustainable path during project implementation (SPD).

√ The total score of sustainable path after project end (SPA).

The ideal sustainable path represents the optimum level of sustainable development and was defined through trade-offs between stakeholders. The stakeholders need to decide through negotiations about the ideal (desired) value of indicators. Figure 22 describes the process of decision making. In all stages of this process of decision making the stakeholders have the ability to trade-off. In addition, stakeholders have the ability to continuously monitor the sustainable path during project implementation. When a project is evaluated from the SD point of view it should be categorized based on the magnitude of its potential environmental, social, economic, technological and (geo)political impacts. Such ranking is based on the categorization process described in Figure 22.

A project's environmental, social, economic, technological and (geo)political due diligence may be considered proportionate to its the nature, scale and stage of the project, and with the level of impacts. The following sustainable development indices can then be determined:

$$\text{"ACROPOLIS 1"} = 100\ (\text{SPA} - \text{SPI}) / |\text{SPI}| \quad (6)$$
$$\text{"ACROPOLIS 2"} = 100\ (\text{SPA} - \text{SPB}) / |\text{SPB}| \quad (7)$$
$$\text{"ACROPOLIS 3"} = 100\ (\text{SPA} - \text{SPD}) / |\text{SPD}| \quad (8)$$

For the purposes of this dissertation, and based on previous work (Kamenopoulos et al. 2015a; 2015b) three project categories arbitrarily have been selected as follows:

- Category A ("Green Code"): Projects with "*ACROPOLIS 1*" index ≥ 75%. This means that the "total score of the sustainable path after project end" is at least 75% of the "total score of the ideal sustainable path". In that case the project has a considerable positive impact in all SD pillars and, thus, it may be evaluated as "GO".

- Category B ("Orange Code"): Projects with 50% ≤ "*ACROPOLIS 1*" index < 75%. Negligible modifications should be proposed to minimize, mitigate and offset minor negative impacts. The project has the potential to be re-assessed.

- Category C ("Red Code"): Projects with "*ACROPOLIS 1*" index < 50%. These projects may have significant environmental, social, economic, technological and geopolitical negative impacts that cannot be currently accepted. Critical changes and modifications are needed before re-evaluation. This evaluation should lead to a "NO GO" decision.

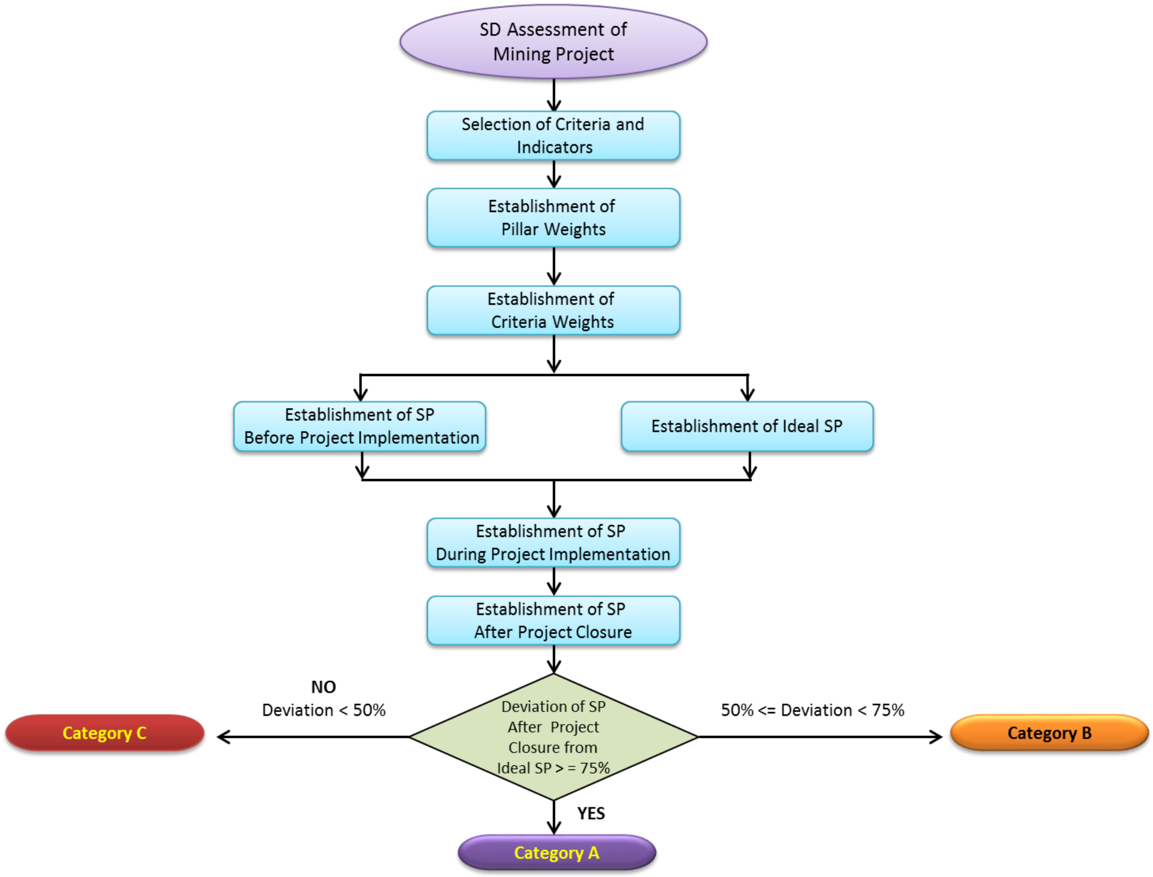

Figure 22 "GO-NO-GO" Decision making process for projects assessment from the Sustainable Development point of view

Indices "*ACROPOLIS 2*" and "*ACROPOLIS 3*" may be utilized by stakeholders as complementary to monitor decision supporting tools. The process that the stakeholders utilize to assign weighting factors for the pillars and criteria (indicators) has five stages:

- In the first stage the stakeholders rank the pillars in terms of their importance from 1 to 5, by assigning an "1" value to the pillar that is most important, and a "5" to the least important.

- In the second stage a fixed number of 10-points are automatically assigned to the least important pillar (pillar ranked as "5"). Then 2x10 points are assigned to the second least important (pillar ranked as "4") and so on. During the third stage the pillar scores are normalized to one in order to obtain the final pillar weighting factors. The scores are normalized by dividing the points assigned to each pillar by the total number of allocated points.

- In the fourth stage the average pillar weightings are calculated for all pillars: the sum of for each pillar weighting factor is divided by the number of stakeholders.

- In the fifth and final stage, the same process is repeated for the establishment of the weighting factors for indicators. The only difference is that during this process the stakeholders rank the indicators in terms of their importance from 1 to 10 by assigning a "1" to the indicator that is most important, and a "10" to the least important indicator.

During this process there are three available levels (opportunities) for trade-offs between stakeholders. At the first level, the stakeholders need to agree on the type of the impact (positive or negative) of each criterion (indicator). At the second level of trade-offs the stakeholders have the chance to modify accordingly their initial preferences on the weighting factor for each pillar. At the third level of trade-offs the stakeholders have the opportunity to modify accordingly their preferences for the weighting factor of each indicator.

After this process, the stakeholders need to agree on the establishment of the Current Sustainable Path by providing the actual current values of indicators (values before the mining project starts). After that the stakeholders need to agree on the establishment of the Ideal Sustainable Path by providing ideal (expected) values of the indicators. During these two processes the stakeholders have another opportunity for trade-offs (fourth level of trade-offs): the stakeholders actually decide mutually which the wanted sustainable paths are. Finally, the ACROPOLIS 1, 2, and, 3 indices are calculated.

For practical reasons, and in order to better understand the above-mentioned methodology, two hypothetical scenarios were constructed and are presented in Appendix B. The first scenario (Scenario 1) is a “NO-GO” scenario: the preferences of the stakeholders are such that the score of ACROPOLIS 1 index is less than 50% (= 32.17%). In this scenario the Sustainable Path after the project is far away from the Ideal Sustainable Path. The project is not sustainable as this may have significant environmental, social, economic, technological and geopolitical negative impacts that cannot be currently accepted by the stakeholders; the Social License to Operate will not be provided by the stakeholders, thus critical changes and modifications are needed before re-evaluation. This evaluation leads to a "NO GO" decision for the specific hypothetical scenario.

The second scenario (Scenario 2) is a "GO" scenario: the preferences of the stakeholders are such that the score of ACROPOLIS 1 index is higher than 75% (= 82.76%). In this scenario the total score of the sustainable path after project end is 82.76% of the total score of the ideal sustainable path. The project may be considered sustainable and the Social License to Operate may be provided by the stakeholders. The evaluation for the specific hypothetical scenario leads to a "GO" decision.

As it was previously mentioned the UN's official definition of Sustainable Development prerequisites the conditions of "…*effective citizen participation in decision making and by greater democracy in international decision making*…". The proposed "*ACROPOLIS* DSS", through its five stages of assigning weightings to pillars and its four trade-off levels, provides several degrees of freedom to stakeholders for "effective citizen participation". Therefore, the likelihood of companies to gain and retain the "Social License to Operate" is assessed. This is not a "white collars-cost" oriented tool. It is rather a "value" oriented tool where stakeholders are encouraged to incorporate and directly or indirectly express their "value" for the stake of the project.

Furthermore, the proposed "ACROPOLIS DSS" provides the ability to quantify and measure the US NRC's term of "sustainable path" which was described as "…*one that allows every future generation the option of being as well off as its predecessors*…" (US NRC, 1994). As a result, it provides a meaningful quantitative interrelation and interconnection between the SD pillars. Additionally, it provides the ability to measure other essential SD pillars such as: Geopolitics and Technology. These SD pillars, although are not recommended by the UN, they are considered extremely important in todays globalized business environment.

The proposed "ACROPOLIS DSS" framework is in a prototype stage. At this stage there are not sufficient actual data available from existing projects to support a sensitivity or parametric analysis. However, if this system is accepted and utilized as a decision making support system, a parametric analysis should be conducted to study its performance by allowing specific parameters to obtain extreme values. For example, if a "GO-NO-GO" decision is to be reached for a project, important questions such as the following would be asked:

- What would be the influence of a pillar's and/or indicator's weighting factor on the "GO-NO-GO" decision making indices?

- How would the SP properties change using trade-offs between stakeholders, while maintaining the same total score for the "GO-NO-GO" decision making index ("*Acropolis 1*" $\geq$ 75%)? For example, what tradeoffs should be made in order to double the "GDP per Capita" but maintain the "*Acropolis 1*" index above 75%? Alternatively, the stakeholders may need to tradeoff and clarify how much they have to modify the SP properties to reduce by half the "Level of Unemployment".

- How much an indicator may change in order to reach a 1% increase of the "*Acropolis 1*" index?"

- If an indicator increases by 1,000 units, by what percentage would the "*Acropolis 1*" index be changed?"

The proposed DSS in its prototype version was designed to include the preferences of five stakeholder groups. It can be easily modified to include a greater number of stakeholders. In the same manner, the proposed DSS was initially designed to support decisions for the five most important SD pillars in order to adapt with the recommended Sustainable Development Framework for Rare Earth Element Mining Projects (Kamenopoulos et al., 2015b); it can be easily modified to include any higher number of SD pillars. The proposed DSS was designed to incorporate ten SD quantitative and qualitative indicators; however, it can be modified to incorporate a greater number of SD qualitative and quantitative indicators.

It should be noted that the proposed DSS was not designed to assess mining projects from their financial or economic value, however it can be modified to also incorporate financial indicators and support the assessment of project costs (Sprecher et al., 2015). Finally, the proposed DSS was designed to support all three stages of a project: before the project starts, during project implementation and after the project terminates. Table 14 describes the arguments for and against the implementation of the proposed "*ACROPOLIS* DSS".

Table 14 Arguments for and against the implementation of the proposed "ACROPOLIS DSS"

For	Against
It provides the stakeholders with the opportunity for transparent, free decision making and democratic negotiations.	No sufficient data yet available for testing/prototype stage.
It quantifies and measures the US NRC's term of "*sustainable path*" which was described as "…*one that allows every future generation the option of being as well off as its predecessors…*"	No sufficient data yet available for testing/prototype stage.
It complies with the UN's SD prerequisite for "…*effective citizen participation in decision making and by greater democracy in international decision making*…"	No sufficient data yet available for testing/prototype stage.
It contributes in gaining and retaining "Social License to Operate".	No sufficient data yet available for testing/prototype stage.
It is a "value" oriented tool: stakeholders are encouraged to incorporate and directly or indirectly express their "value" on the stake of the project	No sufficient data yet available for testing/prototype stage.
It is designed to support all three stages of a project: before, during and after project's termination.	No sufficient data yet available for testing/prototype stage.
If modified, it may include any number of SD pillars.	It was built for five SD pillars. Need modifications/prototype stage.
If modified, it may include unlimited number of stakeholders.	It was built for five stakeholders. Need modifications/prototype stage.
If modified, it may include unlimited number of indicators.	It was built for 10 indicators per each pillar. Need modifications/prototype stage.
If modified, it could also incorporate financial indicators.	Not designed to assess projects from their financial/economic value.
It incorporates qualitative and quantitative indicators.	No sufficient data yet available for testing/prototype stage.
If modified, it may be applicable in any project. Not necessarily in mining sector.	Need modifications/prototype stage.
Utilizing parametric analysis the stakeholders may be provided with additional useful information.	No sufficient data yet available/prototype stage.

Chapter 9. Conclusions

During this research the relevant importance of REEs in terms of trade, the number of initiatives related to REEs made in the US and EU, the number of geopolitical events/reports related to REEs, and in terms of the level of REEs mitigation was investigated. The stream mapping of the REEs production process was developed followed by the identification of stakeholders and the detection of hazards/vulnerabilities of REEs production. A framework was proposed for the Sustainable Development of REEs mining projects. This framework incorporated five basic "overlapping" circles: economy, society, environment, technology, and (geo)politics. The proposed framework also includes three controlling/limiting factors: policy, governance, and stakeholders, and indicators to be used in decision making. Furthermore, to better encapsulate the concept of sustainable path, the "Swiss Cheese" model of accidents was adopted. Finally, the "overlapping" circles of SD are proposed to be examined from their vertical intersection. This new approach provides a practical vision and better understanding of the SD Path, the quantification of the deviation from the ideal SD path, the "go-no-go" ability to SD decision makers and the ability to avoid latent SD conditions.

In addition, the following were established:

- China is considering a dominant player in REEs world production (up to 97%- 99.8%).
- The US, EU and Japan are the major importers of Chinese REEs
- China's demand for REEs was estimated that will reach its production level by the year 2012
- The main end uses of REEs include the energy and defense sectors.
- Applications of REEs may provide low cost and energy efficiencies.
- A large number of REEs-related initiatives have been made since 2010 in EU and US.
- The substitution of REEs is rare and/or impossible and/or in preliminary status.
- The recycling potential of REEs suffers by a number of constraints.
- A significant number of critical geopolitical events/reports related to REEs have been identified since 2010.
- The Stream Mapping of REEs Production process includes the ore mining, crushing, grinding, floatation, chemical processing, purification and manufacture.

- The main stakeholders ("players") in the production of REEs are the mining companies, the environment, the markets, the public, the governments/NGOs, the employees, and the media.
- From the environmental perspective, mining of REEs is expected to be similar to any other hard rock mining procedures. Except for the radioactivity of uranium/thorium the potential waste emissions would be comparable to a typical hard rock mine.
- Media plays a major role as a stakeholder in REEs production. The role of media would be negative and/or positive.
- Main factors that affect the market of REEs would be the dominance of China in REEs production, the demand/supply/prices mix, the export restrictions, smuggling, badly implemented policies, reluctant and/or complete lack of environmental and labor regulations in China, the strict environmental safety, health and labor regulations in the west, the status of global economy/growth, the fact that REEs are not traded through Market or Metal Exchanges, the (geo)politics, the fact that substitution of REEs is rare and/or impossible and/or in preliminary status, and the fact that the recycling potential of REEs suffers by a number of constraints.
- Several hazards exist at each process of REEs production. Amongst others are the following: air dust, radiation, CO2 emissions, heavy metals/acids/fluorides to surface/groundwater/soil, and common occupational safety & health hazards.
- The effect of these hazards/vulnerabilities is expected to incorporate all stakeholders ("players").

This research proposed a framework for evaluating the conformance of REEs mining/processing projects to SD principles. This framework, which incorporates five basic elements, namely, economy, society, environment, technology, and (geo)politics, may be more widely applicable than the case considered here. The proposed framework also includes three controlling/limiting factors, i.e., policy, governance, and stakeholders, as well as indicators to be used in decision making. Furthermore, to better encapsulate the concept of sustainable path, the "Swiss Cheese" model of accidents was adopted. Finally, it is proposed that the "overlapping" circles (or pillars) of SD which can be of different size, should be evaluated by examining a cross-section through which a sustainability path may be identified.

This new approach provides a practical vision and better understanding of the SD Path, the quantification of the deviation from the ideal SD path, the "go-no-go" ability to SD decision makers and the ability to avoid latent SD conditions. In addition, it was explained how the generic SD framework can be applied in the case of REEs.

The ability of a mining firm to gain social license to operate depends on the presence of a stable economy, balanced social expectations, i.e., a fair distribution of benefits and risk, and trust. Often trust is undermined by a lack of transparency. Conversely, following a path of clear communication, utilizing SD C&I, combined with sustainable mining practices, makes it easier to establish trust and gain a social license to operate. The bonding material that ensures the clear communication among stakeholders (firm, government, civil society), and the clarity of messages, is an agreed upon set of SD C&I relevant to the situation at hand.

Since the late 1990's considerable effort has been put into developing sustainability C&I for the minerals sector. Major mining firms have largely settled on using some or all of the basic GRI indicators plus the Mining and Metals Sector Supplement. Reporting based on this framework contains a great deal of information, typically aggregated across all of a firm's operations, but does not directly include data that specifically addresses the particularities of REEs mining.

REEs mining is characterized by particular technical, economic, and geopolitical characteristics. Looking first at the technical issues, REEs ores usually contain thorium or uranium, which needs to be dealt with in a safe manner. There are also numerous ore types, each of which needs to be handled in a specific and appropriate manner. As a result, unlike for example coal or copper mining, broadly applicable standards of best practice are not currently available. Concerns about how radiation and environmental impacts will be managed has led to opposition to REEs mining in some locations. Public fears are not unwarranted; there have been numerous instances of REEs mines that have polluted the environment, particularly, though not exclusively, in China.

Five other particularities of REEs mining have been identified: market importance, smuggling, illegal mining, media attention, and Chinese market dominance. Each of these has the potential to impact any or all of the five pillars of sustainability: environment, economy, society, technology, and geopolitics. When taken as a whole, the particularities create a uniquely challenging situation for firms trying to develop new REEs mines.

To assist in communication and information sharing among stakeholders, thirty one supplementary C&I have been created, intended for use in conjunction with GRI-based indicators. The C&I pairs span the five SD pillars, i.e., the environment pillar with 3 C&I, the economy pillar with 10 C&I, the society pillar with 9 C&I, the technology pillar with 4 C&I, and the geopolitical pillar with 5 C&I. The rationale for criteria inclusion, the impact on sustainability (positive or negative) of these criteria and the related measure are also discussed in this chapter.

The C&I pairs address the particularities of REEs mining projects and, given a clear communication path between stakeholders, will on one hand assist future policy makers on decisions regarding the extraction of REEs and, on the other hand, will influence the project's ability to gain and retain social license to operate. Furthermore, this new set of criteria and indicators should be viewed as a base tool, which can be enhanced, modified and / or tailored to a specific project. More generally, they will support analysis of a REEs mining project's contribution to sustainable development, including how the mine would contribute to the achievement of the UN SDGs in a specific location. This would be beneficial because mining has the potential to be a catalyst for and driver of sustainable economic development, but current reporting protocols do not capture this adequately. Moreover, if a firm can demonstrate through reporting that a REEs mine is likely to positively contribute to society, it is much more likely to gain a social license to operate.

The approach that has been taken here could be adapted to other mineral mining circumstances where unique problems are present. For example, there is considerable interest in seabed mining. The generic GRI and MMSS do not capture all of the information that would need to be collected and shared about such a mining project.

The limitations of the study rest mainly in three areas. First, the SDGs are still under development, with debate in the UN General Assembly expected during the summer of 2015. It is possible that the indicator set will need to be revised or amended should the UN GA make significant changes to the SDGs that have been proposed by the Open Working Group. Moreover, the body of literature on C&I for the SDGs is limited. The measures proposed for each C&I may need to be reconsidered as additional research is undertaken and published in the peer reviewed literature. Second, the supplementary C&I will require data collection, an expensive undertaking that some firms may resist. Finally, it is unclear whether state-controlled mining firms in some parts of the world will be motivated commit to extended reporting since they may not need a social license to operate, unlike publicly traded firms.

The 2030 Agenda for Sustainable Development of the United Nations set out 17 SDGs that require creativity and innovation to meet SD challenges. So far, a number of DSS models have been applied in several SD concepts utilizing different methodologies and techniques. In this dissertation a state-of-the-art DSS ("*ACROPOLIS* DSS") was proposed which can assist decision makers and stakeholders to evaluate a project and make "GO-NO-GO" decisions from the SD point of view. This work integrates the proposed all-purpose DSS into a recommended Sustainable Development Framework. The presented DSS is based on Multi-criteria Decision Analysis and Multi-attribute Utility Theory and provides the ability to approach the sustainability concepts of "*citizen participation*", and "*greater transparency*" in decision making in a holistic quantified manner as described and recommended in earlier years by the United Nations. In addition, the proposed DSS provides the ability to trace, quantify and measure the concept of "*sustainable path*" as defined by the U.S National Research Council.

The innovation of the proposed DSS is evident when considering the following:

- It provides stakeholders with the opportunity for transparent, free decision making and open negotiations within several stages of weighting factor calculations and numerous levels of trade-offs as this is required by the definition of Sustainable Development. These conditions may increase the likelihood of companies to gain and retain the Social License to Operate.

- It is designed to properly combine quantified indicators before the implementation of a project and forms the baseline for a SD evaluation during after the implementation of any mining project as well as after its end.

The proposed DSS is still in a prototype form but sets the stage for what needs to be considered when mining projects stall due to a number of conflicts. It is clear that further research is necessary towards the goal of a uniformly accepted DSS for the design and implementation of mining projects under the principles of Sustainable Development. The author will continue to develop the proposed DSS and test its applicability to different projects.

Chapter 10. References

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APPENDIX A

Figure A1 show the basket price evolution of ten rare earth elements between years 2009 and 2016. Source: Arafura Resources Limited, at: http://www.arultd.com/rare-earths/pricing.html, and Haque et al., 2014.

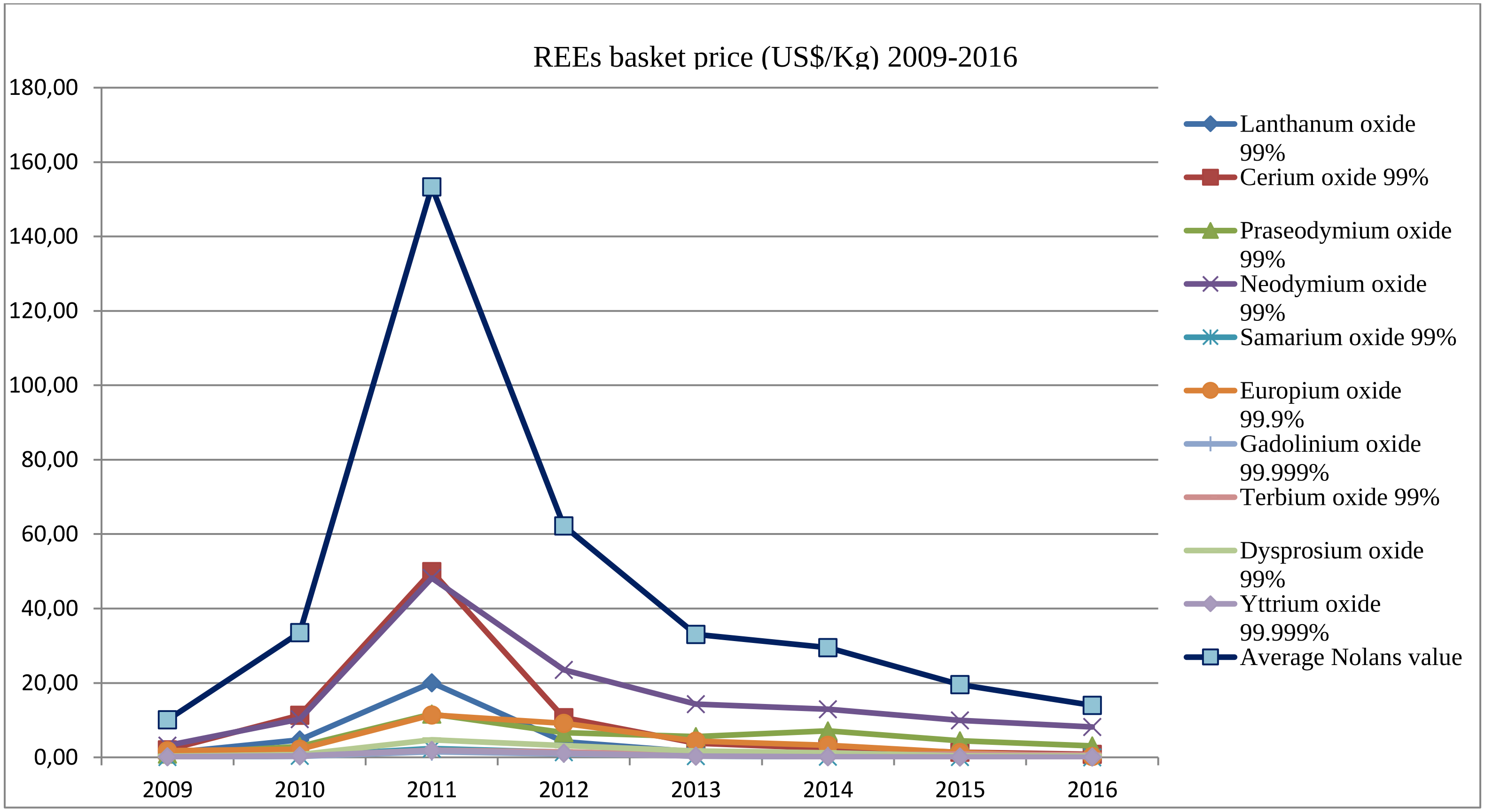


Figure A1. REEs Basket Price (USD/kg) 2009-2016. Average REEs value represents the sum of contributions by individual REOs (source: Arafura Resources Limited, at: http://www.arultd.com/rare-earths/pricing.html, and Haque et al., 2014)

APPENDIX B

Tables B1 through B5 represent a hypothetical “NO-GO” scenario. They show the values of pillar and criteria weights in accordance to five stakeholders ranking preferences and specific values of indicators.

Tables B6 through B10 represent a hypothetical “GO” scenario. They show the values of pillar and criteria weights in accordance to five stakeholders ranking preferences and specific values of indicators.

Figures B1 and B2 shows two screens of the actual DSS for the “NO-GO” scenario.

Figures B3 and B4 shows two screens of the actual DSS for the “GO” scenario.

Hypothetical scenario 1 (NO-GO decision)

Table B1. Hypothetical scenario 1 (NO-GO RESULT): Pillars weights in accordance to five stakeholder ranking preferences and specific values of indicators

Pillars weights	Stakeholder 1	Stakeholder 2	Stakeholder 3	Stakeholder 4	Stakeholder 5
Environment	0.06	0.08	0.08	0.05	0.05
Economy	0.29	0.08	0.15	0.25	0.24
Society	0.29	0.38	0.31	0.25	0.24
Technology	0.29	0.38	0.38	0.25	0.24
Geopolitics	0.06	0.08	0.08	0.20	0.24

Table B2. Hypothetical scenario 1 (NO-GO RESULT): Average pillars weights in accordance to five ranking stakeholder preferences and specific values of indicators

Pillars	Average pillars weights
Environment	0.06
Economy	0.20
Society	0.29
Technology	0.31
Geopolitics	0.13

Table B3. Hypothetical scenario 1 (NO-GO RESULT): Average criteria weights in accordance to five stakeholder ranking preferences and specific values of indicators

Pillar	Criteria	Average criteria weights
Environment	Toxic contamination	0.33
	Radiation (Public Exposure)	0.33
	Radiation (Occupational Exposure)	0.33
Economy	Resource rent	0.11
	Agriculture	0.10
	Industrial development	0.12
	Tourism	0.12
	Settlements	0.08
	Infrastructure & transportation	0.12
	Economic diversity	0.09
	Entrepreneurship I	0.08
	Entrepreneurship II	0.08
	Access to energy	0.09
Society	Community life	0.18
	Health and population	0.09
	People's happiness and well-being	0.11
	Human development	0.11
	Human Rights	0.11
	Family life	0.11
	Access of local people/society to vital resources: food/water security	0.11
	Income/poverty	0.10
	Activism	0.10
Technology	Availability of skilled work-	0.29

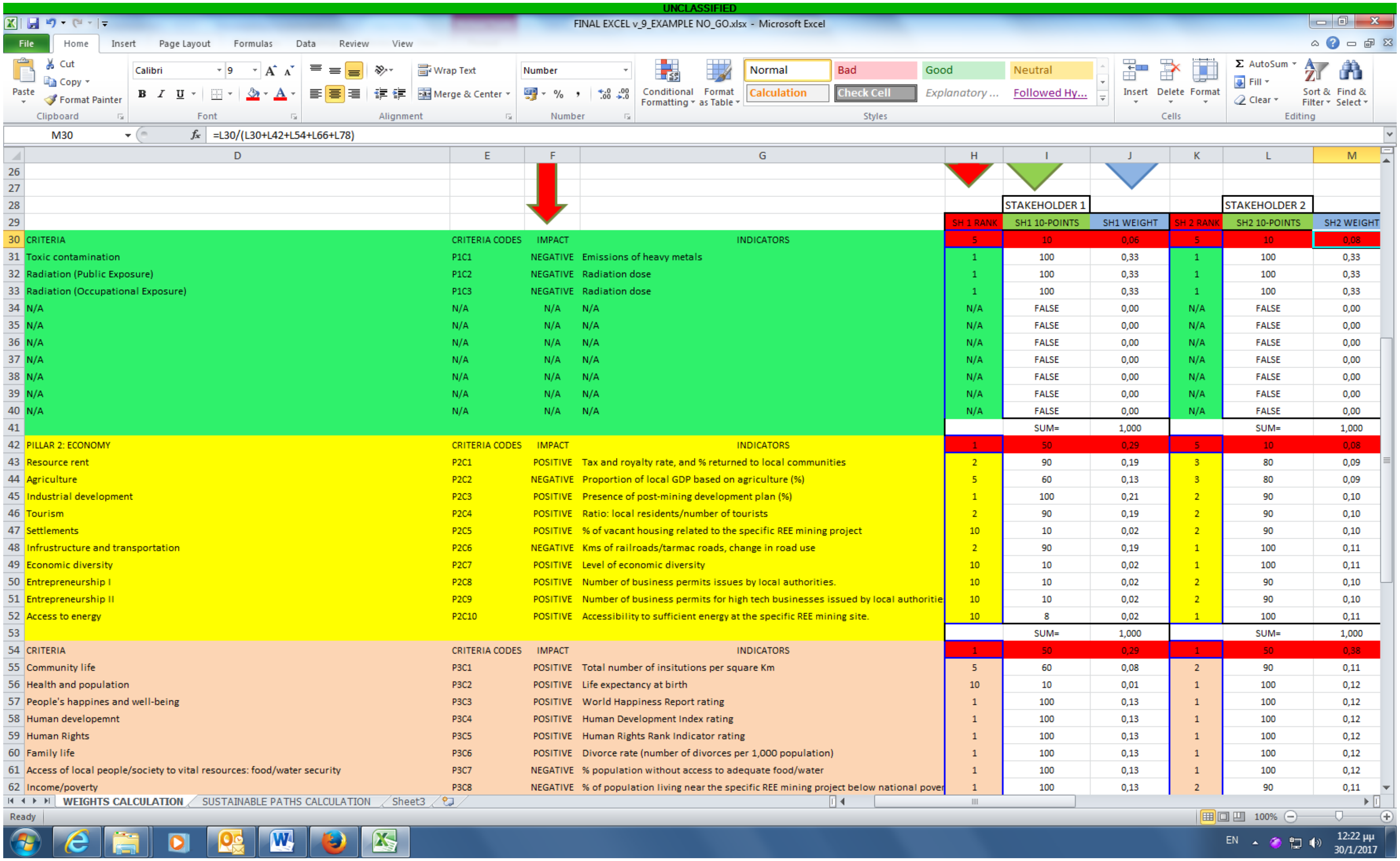
	force	
	Innovation I	0.23
	Innovation II	0.24
	Innovation III	0.24
Geopolitics	Political stability and security	0.20
	Global secure of REEs supply	0.17
	Quality of democracy I	0.22
	Quality of democracy II	0.22
	Quality of democracy III	0.20

Table B4. Hypothetical scenario 1 (NO GO RESULT): Values of Sustainable Paths (SP) in accordance to five stakeholder ranking preferences and specific values of indicators

Sustainable paths	Value
SD before project	26.81
Ideal SD path	30.38
SD during project	29.01
SD after project	40.15

Table B5. Hypothetical scenario 1 (NO GO RESULT): Values of ACROPOLIS indices and final result in accordance to five stakeholder ranking preferences and specific values of indicators

Acropolis indices	Value	Result
Acropolis 1	32.17 << 50%	NO GO
Acropolis 2	49.75	
Acropolis 3	38.40	



	D	E	F	G	H	I	J	K	L	M
28						STAKEHOLDER 1			STAKEHOLDER 2	
29					SH 1 RANK	SH1 10-POINTS	SH1 WEIGHT	SH 2 RANK	SH2 10-POINTS	SH2 WEIGHT
30	CRITERIA	CRITERIA CODES	IMPACT	INDICATORS	5	10	0,06	5	10	0,08
31	Toxic contamination	P1C1	NEGATIVE	Emissions of heavy metals	1	100	0,33	1	100	0,33
32	Radiation (Public Exposure)	P1C2	NEGATIVE	Radiation dose	1	100	0,33	1	100	0,33
33	Radiation (Occupational Exposure)	P1C3	NEGATIVE	Radiation dose	1	100	0,33	1	100	0,33
34	N/A	N/A	N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00
35	N/A	N/A	N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00
36	N/A	N/A	N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00
37	N/A	N/A	N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00
38	N/A	N/A	N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00
39	N/A	N/A	N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00
40	N/A	N/A	N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00
41						SUM=	1,000		SUM=	1,000
42	PILLAR 2: ECONOMY	CRITERIA CODES	IMPACT	INDICATORS	1	50	0,29	5	10	0,08
43	Resource rent	P2C1	POSITIVE	Tax and royalty rate, and % returned to local communities	2	90	0,19	3	80	0,09
44	Agriculture	P2C2	NEGATIVE	Proportion of local GDP based on agriculture (%)	5	60	0,13	3	80	0,09
45	Industrial development	P2C3	POSITIVE	Presence of post-mining development plan (%)	1	100	0,21	2	90	0,10
46	Tourism	P2C4	POSITIVE	Ratio: local residents/number of tourists	2	90	0,19	2	90	0,10
47	Settlements	P2C5	POSITIVE	% of vacant housing related to the specific REE mining project	10	10	0,02	2	90	0,10
48	Infrustructure and transportation	P2C6	NEGATIVE	Kms of railroads/tarmac roads, change in road use	2	90	0,19	1	100	0,11
49	Economic diversity	P2C7	POSITIVE	Level of economic diversity	10	10	0,02	1	100	0,11
50	Entrepreneurship I	P2C8	POSITIVE	Number of business permits issues by local authorities.	10	10	0,02	2	90	0,10
51	Entrepreneurship II	P2C9	POSITIVE	Number of business permits for high tech businesses issued by local authoritie	10	10	0,02	2	90	0,10
52	Access to energy	P2C10	POSITIVE	Accessibility to sufficient energy at the specific REE mining site.	10	8	0,02	1	100	0,11
53						SUM=	1,000		SUM=	1,000
54	CRITERIA	CRITERIA CODES	IMPACT	INDICATORS	1	50	0,29	1	50	0,38
55	Community life	P3C1	POSITIVE	Total number of insitutions per square Km	5	60	0,08	2	90	0,11
56	Health and population	P3C2	POSITIVE	Life expectancy at birth	10	10	0,01	1	100	0,12
57	People's happines and well-being	P3C3	POSITIVE	World Happiness Report rating	1	100	0,13	1	100	0,12
58	Human developemnt	P3C4	POSITIVE	Human Development Index rating	1	100	0,13	1	100	0,12
59	Human Rights	P3C5	POSITIVE	Human Rights Rank Indicator rating	1	100	0,13	1	100	0,12
60	Family life	P3C6	POSITIVE	Divorce rate (number of divorces per 1,000 population)	1	100	0,13	1	100	0,12
61	Access of local people/society to vital resources: food/water security	P3C7	NEGATIVE	% population without access to adequate food/water	1	100	0,13	1	100	0,12
62	Income/poverty	P3C8	NEGATIVE	% of population living near the specific REE mining project below national pover	1	100	0,13	2	90	0,11

Figure B1: Indicative screen for the hypothetical NO-GO scenario: ranking of pillars and criteria in accordance to preferences of stakeholders 1 and 3.

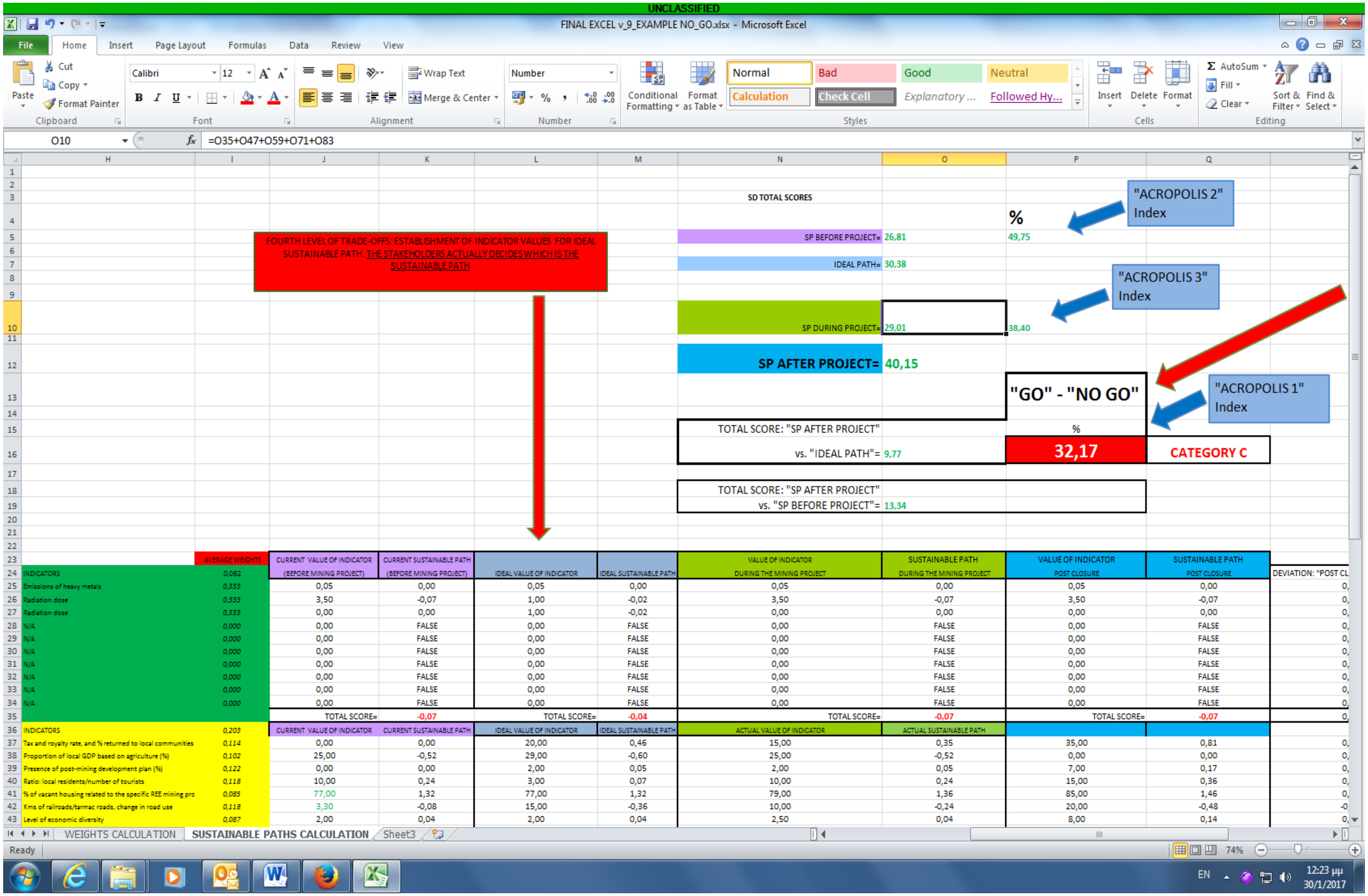


Figure B2: Indicative screen for the hypothetical NO-GO scenario: results of ranking process.

Hypothetical scenario 2 (GO decision)

Table B6. Hypothetical scenario 2 (GO RESULT): Pillars weights in accordance to five stakeholder ranking preferences and specific values of indicators

Pillars weights	Stakeholder 1	Stakeholder 2	Stakeholder 3	Stakeholder 4	Stakeholder 5
Environment	0.24	0.20	0.20	0.20	0.06
Economy	0.15	0.26	0.26	0.26	0.29
Society	0.24	0.07	0.07	0.07	0.06
Technology	0.19	0.33	0.33	0.33	0.29
Geopolitics	0.14	0.33	0.33	0.33	0.29

Table B7. Hypothetical scenario 2 (GO RESULT): Average pillars weights in accordance to five ranking stakeholders preferences and specific values of indicators

Pillars	Average pillars weights
Environment	0.13
Economy	0.25
Society	0.10
Technology	0.26
Geopolitics	0.25

Table B8. Hypothetical scenario 2 (GO RESULT): Average criteria weights in accordance to five stakeholder ranking preferences and specific values of indicators

Pillar	Criteria	Average criteria weights
Environment	Toxic contamination	0.33
	Radiation (Public Exposure)	0.33
	Radiation (Occupational Exposure)	0.3
Economy	Resource rent	0.10
	Agriculture	0.11
	Industrial development	0.10
	Tourism	0.10
	Settlements	0.10
	Infrastructure & transportation	0.10
	Economic diversity	0.10
	Entrepreneurship I	0.10
	Entrepreneurship II	0.10
	Access to energy	0.09
Society	Community life	0.11
	Health and population	0.11
	People's happiness and well-being	0.11
	Human development	0.11
	Human Rights	0.11
	Family life	0.11
	Access of local people/society to vital resources: food/water security	0.11
	Income/poverty	0.11
	Activism	0.10
Technology	Availability of skilled work-force	0.25
	Innovation I	0.25

	Innovation II	0.25
	Innovation III	0.25
Geopolitics	Political stability and security	0.19
	Global secure of REEs supply	0.21
	Quality of democracy I	0.20
	Quality of democracy II	0.20
	Quality of democracy III	0.19

Table B9. Hypothetical scenario 2 (GO RESULT): Values of Sustainable Paths (SP) in accordance to five stakeholder ranking preferences and specific values of indicators

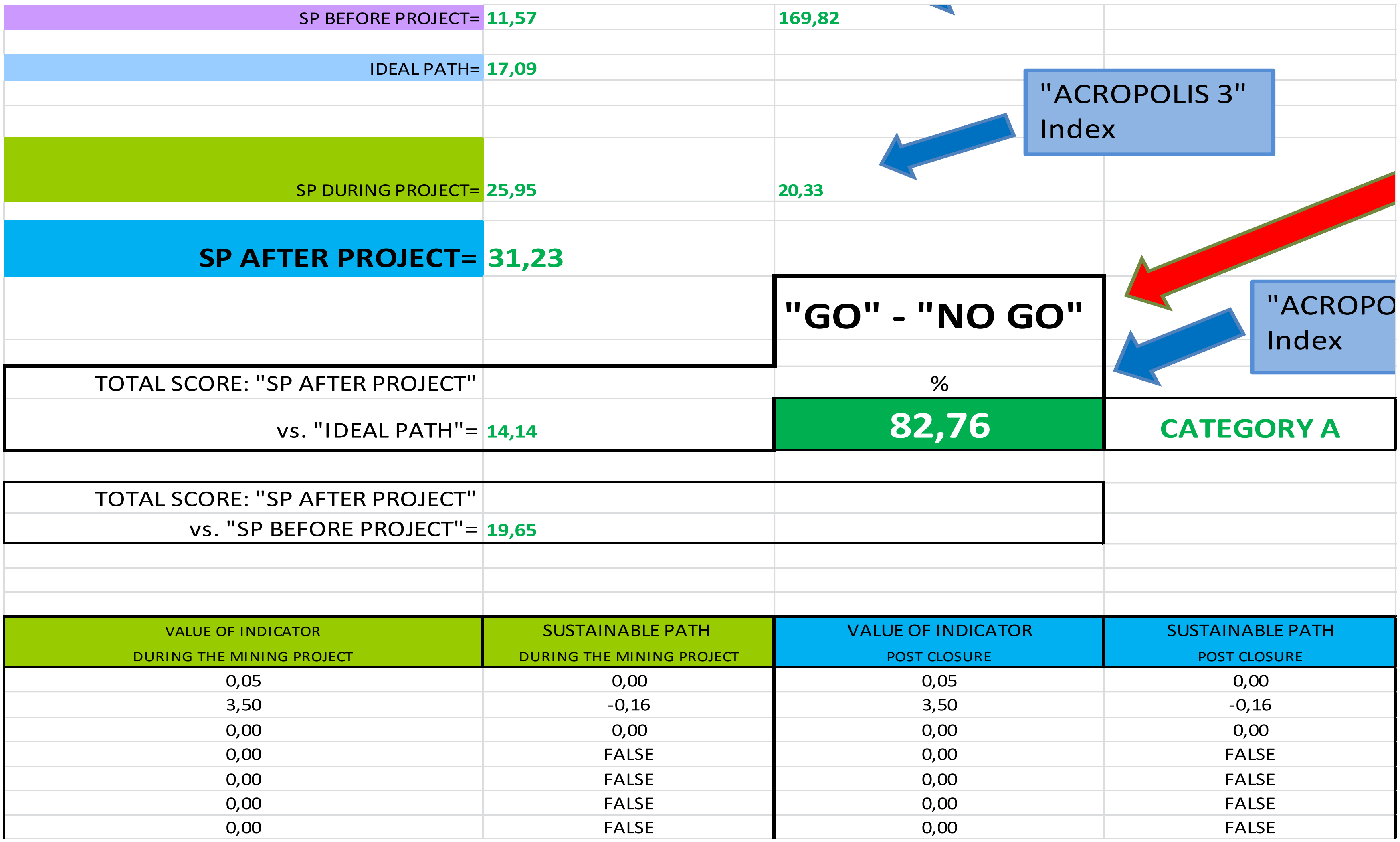
Sustainable paths	Value
SD before project	11.57
Ideal SD path	17.09
SD during project	25.95
SD after project	31.23

Table B10. Hypothetical scenario 2 (GO RESULT): Values of ACROPOLIS indices and final result in accordance to five stakeholder ranking preferences and specific values of indicators

Acropolis indices	Value	Result
Acropolis 1	82.76 > 75%	GO
Acropolis 2	169.82	
Acropolis 3	20.33	

			STAKEHOLDER 1			STAKEHOLDER 2			STAKEHOLDER 3	
		SH 1 RANK	SH1 10-POINTS	SH1 WEIGHT	SH 2 RANK	SH2 10-POINTS	SH2 WEIGHT	SH 3 RANK	SH3 10-POINTS	SH3 WEIGHT
IMPACT	INDICATORS	1	50	0.24	3	30	0,16	3	30	0,16
NEGATIVE	Emissions of heavy metals	1	100	0,33	5	60	0,33	5	60	0,33
NEGATIVE	Radiation dose	1	100	0,33	5	60	0,33	5	60	0,33
NEGATIVE	Radiation dose	1	100	0,33	5	60	0,33	5	60	0,33
N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00	N/A	FALSE	0,00
N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00	N/A	FALSE	0,00
N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00	N/A	FALSE	0,00
N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00	N/A	FALSE	0,00
N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00	N/A	FALSE	0,00
N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00	N/A	FALSE	0,00
N/A	N/A	N/A	FALSE	0,00	N/A	FALSE	0,00	N/A	FALSE	0,00
			SUM=	1,000		SUM=	1,000		SUM=	1,000
IMPACT	INDICATORS	3	30	0,15	1	50	0,26	1	50	0,26
POSITIVE	Tax and royalty rate, and % returned to local communities	5	60	0,10	1	100	0,10	2	90	0,10
NEGATIVE	Proportion of local GDP based on agriculture (%)	2	90	0,16	1	100	0,10	2	90	0,10
POSITIVE	Presence of post-mining development plan (%)	5	60	0,10	1	100	0,10	2	90	0,10
POSITIVE	Ratio: local residents/number of tourists	5	60	0,10	1	100	0,10	3	80	0,09
POSITIVE	% of vacant housing related to the specific REE mining project	5	60	0,10	1	100	0,10	2	90	0,10
NEGATIVE	Kms of railroads/tarmac roads, change in road use	5	60	0,10	1	100	0,10	2	90	0,10
POSITIVE	Level of economic diversity	5	60	0,10	1	100	0,10	2	90	0,10
POSITIVE	Number of business permits issues by local authorities.	5	60	0,10	1	100	0,10	2	90	0,10
POSITIVE	Number of business permits for high tech businesses issued by local authorities	5	60	0,10	1	100	0,10	1	100	0,11
POSITIVE	Accessibility to sufficient energy at the specific REE mining site.	1	8	0,01	1	100	0,10	1	100	0,11
			SUM=	1,000		SUM=	1,000		SUM=	1,000

Figure B3: Indicative screen for the hypothetical GO scenario: ranking of pillars and criteria in accordance to preferences of stakeholders 1 through 3.



VALUE OF INDICATOR DURING THE MINING PROJECT	SUSTAINABLE PATH DURING THE MINING PROJECT	VALUE OF INDICATOR POST CLOSURE	SUSTAINABLE PATH POST CLOSURE
0,05	0,00	0,05	0,00
3,50	-0,16	3,50	-0,16
0,00	0,00	0,00	0,00
0,00	FALSE	0,00	FALSE
0,00	FALSE	0,00	FALSE
0,00	FALSE	0,00	FALSE
0,00	FALSE	0,00	FALSE

Figure B4: Indicative screen for the hypothetical GO scenario: results of ranking process.