



**Politecnico
di Torino**

ScuDo

Scuola di Dottorato ~ Doctoral School

WHAT YOU ARE, TAKES YOU FAR

Doctoral Dissertation
Doctoral Program in Energy Engineering (35th Cycle)

Critical raw materials and strategic technologies. Theoretical and practical approaches towards the green transition

Umberto Eynard

Supervisor

Prof. Gian Andrea Blengini

Doctoral Examination Committee

Prof. George Barakos - Curtin University (Australia) - Referee

Prof. Antoine Beylot - Bureau de Recherches Géologiques et Minières (France) - Referee

Politecnico di Torino

October 24, 2023

This thesis is licensed under a Creative Commons License, Attribution - Noncommercial - NoDerivative Works 4.0 International: see www.creativecommons.org. The text may be reproduced for non-commercial purposes, provided that credit is given to the original author.

I hereby declare that, the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

A handwritten signature in black ink, enclosed in a rectangular box with a dashed line at the bottom. The signature appears to read 'Umberto Eynard'.

Umberto Eynard
Turin, October 24, 2023

Abstract

The transition towards a climate neutral economy by 2050 and EU's commitments to global climate action under the Paris agreements are determining important changes in the European industrial ecosystems with unprecedented effects to the environment and the society.

The development of strategic technologies towards a green and digital future requires growing quantities of energy and critical raw materials for their deployment at a larger scale.

An additional fact is the particular period in history that has characterized years since 2019. At a short distance in time two important disruptive events struck Europe such as the Covid-19 pandemic and then the conflict inside Ukrainian territories in 2022. Both determined an increased geopolitical instability and scenarios that were previously considered simple possibilities have become the reality. Alongside the sustainability objectives as defined by the United Nations Sustainable Development Goals and the European Green Deal, the concepts of self-sufficiency, resilience and strategic autonomy have gained increasing importance within the policy agendas. This has accelerated the need to produce sound mechanisms to give timely and effective answers and at the same time has posed the question how and to which degree the theoretical approaches proposed in the past can be at the height of present expectancy.

Critical raw materials are one of the fundamental blocks of this transition period and their management at political level is influencing the different dimensions of future technological, environmental and social challenges and geopolitical stability.

The dissertation investigates the role of methodologies, software tools and indicators to obtain results in terms of evaluations, choices, decisions, and actions in the path towards the climate neutrality transition considering the role of critical

raw materials and strategic technologies in four different dimensions: technological, environmental, social and geopolitical.

Based on several theoretical approaches and practical calculation techniques defined in literature, this work gathers and analyses the methods and software tools and indicators that have been developed or applied in a three years period from 2019-2023. All tools are used to investigate problems of the four considered dimensions related to raw materials supply, such as their environmental compatibility, social impacts and ensure sustainable practises also through innovative technologies and circular economy strategies. Particularly innovative here are the considerations on circular economy mitigation strategy in addition to recycling with the proposal of a circularity index, the development of a bridging tool as a combination of criticality assessment, material flow analysis and life cycle assessment, and the conversion of environmental footprint method into policy requirements for Photovoltaics. A multi-criteria approach is considered as a *conditio sine qua non* to quantitatively understand the complexity of globalised value chains and to provide policy makers with reliable results and solid arguments. This brings us to interpret the various approaches, methodologies, software tools and indicators as components of a toolbox.

Tools can be selected and grouped together in a toolbox with rather homogeneous categories that can help choose which is more adequate to use situation per situation and suggest improvements based on commonalities and differences.

Although improvable in the future, the novelty of this work is the comparative analysis of tools and their application with the identification of profiles and scenarios. This method of analysis and categorization could be reviewed along with the introduction of new tools and the increase in complexity of the problems that shall be faced in relation with green transition. This plethora has stimulated the interest to widen the knowledge and deepen the comparative and integrative analysis, although these are the first hints. In particular the availability and quality of data appears to be considered one of the most critical aspects that influence the reliability and significance of results. The toolbox represents a didactic value, since the analysis of critical raw materials needs to take into account all these views. Finally, further research is required to enlarge the set of tools under study considering future evolutions, applications, their interoperability and integration, especially if a path towards input data standardisation could prove successful.