UNIVERSITÀ DEGLI STUDI DI PADOVA

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Recycling of critical materials for the renewable energy sectors: technology analysis and supply chain modelling

Relatore: Prof. Fabrizio Bezzo

Correlatori: Dr. Federico d'Amore,

Ing. Daniel Crîstiu

Laureando: Francesco Dal Pont

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Abstract

In recent years there has been a substantial increase in the average mineral demand, attributable to the growing share of renewable energy sources, which require higher quantities of critical raw materials compared to their fossil fuel-based counterparts. This sharp increase may lead to several challenges that need to be faced, such as fluctuating prices, supply chain bottlenecks, and geopolitical tensions. Furthermore, most critical raw materials are extracted and processed abroad, thus making their supply affected by several uncontrollable factors. The development of recycling technologies for critical raw materials may help mitigating the problem. The purpose of this work is therefore the development of supply chain models for the critical raw materials (CRM) contained in three different technologies, encompassing also their recycle processes, in different scenarios, in years 2030 and 2050. The focus will be on photovoltaic (PV) panels, lithium batteries from electric vehicles (EV) and rare earth magnets from wind turbines and electric vehicles (EV), in the Italian geographic area. The primary outcomes of the supply chain optimization encompass the identification of locations for various recycling plants across different analyzed scenarios.

Specifically, in the 2030 base case scenario, two recycling plants are installed for PV panels, three for EV lithium batteries, and one for NdFeB magnets. The total cost for this scenario amounts to 65 M€/year. In the scenarios projected for the year 2050, the average total cost escalates to 155 M€/year. These costs encapsulate both transportation and processing expenses.

A comparative analysis with the market prices of the CRM yields promising results, as the recycling costs are found to be lower than the current market prices for nearly all the CRM.

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Nomenclature

Mathematical symbols (parameters and variables)

SR = supply risk (-);
EI = economic importance (-);
VA = value added (-);
A_s = end use share of a material in a NACE Rev. 2 sector (-);
Q_s = VA of the sector at the NACE Rev. 2 (-);
SI_{EI} = raw material substitution index for the EI (-);
SCP = substitute cost performance (-);
GS = global supply (-);
$EU_{sourcing}$ = actual sourcing of the EU supply (-);
HHI = Herfindhal-Hirschman Index, representing country concentration (-);
WGI = World Governance Index (-);
IR = import reliance (-);
SI_{SR} = substitution index for the SR (-);
EoL_{RIR} = recycling input rate for end-of-life equipment (%);
IM = import (t/year);
EX = export (t/year);
DP = domestic production (t/year);
t_c = trade-related variable of country c for a candidate raw material (-);
EQ_c = export physical quota imposed by country c (-);
EP_c = export prohibition introduced by country c (-);
$ET\text{-}TA_c$ = export tax imposed by country c (-);
SP_i = substitute production (-);
SC_r = criticality of the substitute (-);
SCo_i = co-production of the sbstitute (-);
CAAGR = compound average annual growth rate (%);

$Lat(n)$ = latitude of all nodes (rad);
$Long(n)$ = longitude of all nodes (rad);
$Q(n,t)$ = availability of waste materials at location n, for technology t (t/year);
$D_{PORTS}(n,np)$ = Ports distances (km]);
$CAP_{min}(t,k)$ = minimum plant capacity for technology t, and size k (t/year);
$CAP_{max}(t,k)$ = maximum plant capacity for technology t, and size k (t/year);
$PC(t,k)$ = plant costs, for technology t and size k (€/t/year);
$TR(t)$ = specific truck costs (€/t/km);
$SH(t)$ = specific barge costs (€/ton/km);
τ = tortuosity factor of the Italian roads (-);
R: Earth radius (km);
$x(n,np,t)$ = quantity to be transported from node n to node np, for technology t (t/year);
$x_t r(n,np,t)$ = quantity to be transported via truck from node n to node np (t/year);
$x\_sh(n,np,t)$ = quantity to be transported via barge from $ports$ to $ports_n$ (t/year);
$x\_av(n,t,k)$ = total quantity arriving to a recycle plant r of technology t and size k (t/year);
TPC_{PV} = total plant costs of all PV panels recycling plants (€/year);
TPC_{BATT} = total plant costs of all EV lithium batteries recycling plants (€/year);
TPC_{MAG} = total plant costs of all NdFeB magnets recycling plants (€/year);
TPC = total plant costs (€/year);
TR_{TRAN}^{PV} = PV panels truck transport costs (€/year);
TR_{TRAN}^{BATT} = EV lithium batteries truck transport costs (€/year);
TR_{TRAN}^{MAG} = NdFeB magnets truck transport costs (€/year);
TR_{TRAN} = total truck transport costs (€/year);
SH_{TRAN}^{PV} = PV panels ship transport costs (€/year);
SH_{TRAN}^{BATT} = EV lithium batteries ship transport costs (€/year)
; SH_{TRAN}^{MAG} = NdFeB magnets ship transport costs (€/year);
SH_{TRAN} = total ship transport costs (€/year);
$TRAN_{TOT}$ = total transport costs (€/year);
$y_{rp}(r,t,k)$ = binary variable, 1 if recycle plant r of technology t and capacity k is installed, 0 otherwise;
$\lambda_{truck}(n,np,t)$ = binary variable, 1 if truck transport is selected from node n to np for technology t, 0 otherwise;
$\lambda_{ship}(n,np,t)$ = binary variable, 1 if ship transport is selected from node n to np for technology t, 0 otherwise.

Model sets

n = set of all 123 nodes in the model;
$p(n)$ = Subset of n comprising the Italian provinces;
$ports(n)$ = Subset of n comprising the main Italian ports;
$p_{\text{sard}}(n)$ = Subset of n comprising Sardinia provinces;
$p_{\text{no sard}}(n)$ = Subset of n comprising all the Italian provinces without Sardinia ones;
$p_{\text{sic}}(n)$ = Subset of n comprising Sicily provinces;
$p_{\text{no sic}}(n)$ = Subset of n comprising all the Italian provinces without Sicily ones;
$t = \{PV, BATT, MAG\}$ = set of the three considered green technologies;
k = set of the five different possible size ranges;
np = alias set of n, useful to distinguish between departure and arrival nodes;
r = alias set of $p(n)$, used for the possible recycling plants locations;
$ports_n(n)$ = alias set of $ports(n)$ used for arrival ports.

Acronyms

PV = photovoltaic;
EV = electric vehicles;
REE = rare earth elements;
WEEE = waste electrical and electronic equipment;
CRM = critical raw material;
HREE = heavy rare earth elements;
LREE = light rare earth elements;
PGM = platinum group metals;
EC = European Commission;
NZE = net zero emissions;
APS = announced pledges scenario;
STEPS = stated policies scenario;
HDS = high demand scenario;
LDS = low demand scenario;

Introduction

The contrast between an energy system driven by clean energy technologies and one relying on traditional hydrocarbon resources is significant. Establishing solar photovoltaic (PV) facilities, wind farms, and electric vehicles (EV) typically demands a higher quantity of minerals compared to their fossil fuel-based counterparts. For instance, a standard electric car necessitates six times the mineral resources required for a conventional vehicle, while an onshore wind installation demands nine times more minerals than a gas-powered electricity plant (IEA, 2022a).
Since 2010, there has been a 50% rise in the average mineral demand for generating a new unit of power capacity, attributable to the growing share of renewable energy sources (IEA, 2022a).
Due to escalating demand and increased prices, the market size of key minerals for energy transition has doubled over the last five years, reaching USD 320 billion in 2022, thus taking a leading position in the mining and metals industry (IEA, 2023a).
This trend opens up new interesting revenue prospects for the industry, generating employment opportunities within society, and helping in diversifying economies that heavily rely on coal.
This sharp increase in their market presents therefore a promising landscape for industrial development, even though different obstacles such as fluctuating prices, supply chain bottlenecks, and geopolitical tensions, have to be faced. These factors combine to pose significant risks to ensuring stable and quick transitions toward sustainable energy. Consequently, numerous regions have enacted diverse policy measures to strengthen the resilience and consistency of critical materials supply (IEA, 2023a).
This topic is strictly correlated to the recycling of these materials, since the generation of huge amounts of waste electrical and electronic equipment (WEEE) is taking place globally.
WEEE hold significant amounts of metals, such as Rare Earth Elements (REE), which can be extracted, reclaimed, and reused. On one side, the process of isolating, recov-

ering, and recycling these metals can bring considerable environmental advantages by reducing the accumulation of hazardous materials in landfills. These materials and their compounds pose potential health risks like increased chances of cancer and neurological disorders (Needhidasan et al., 2014).
Additionally, repurposing them in higher-value materials, meeting technological standards, can result in economic and societal gains, allowing to reduce pressure on the supply activities, in particular on the mining sector.
The purpose of this work is therefore the development of supply chain models for the critical raw materials contained in three different technologies, encompassing also their recycle processes. The focus will be on photovoltaic (PV) panels, wind turbines, and electric vehicles (EV), collectively constituting a significant portion of clean energy technologies.
In particular for the EV the recycling of the lithium batteries will be considered, together with the NdFeB permanent magnets contained in the vehicles. These rare earth magnets are present also in wind turbines, hence for this technology, the recycling of the materials constituting these magnets will be considered.
The developed model will perform an economical optimisation of the supply chain, considering the transport of waste equipment of the different technologies from the collection points to the recycling plants, together with the actual recycling processes of the three different green technologies. In Italy, the state of CRM recycling is still in its infancy. Thus, the primary focus of this thesis will be to evaluate the economic viability of recycling methods for CRM, while identifying optimal locations and material flows that define the Italian CRM supply chain. The first Chapter of this work, presents the motivations of the thesis, with an overview of the European situation concerning CRM. Then, the actual definition of CRM is reported, together with an overview of the data utilised in this research. After that, the objectives of the thesis are declared. In Chapter 2 an analysis of the recycling processes for the three mentioned green technologies is reported. An overview of the state of art is presented, together with more technical aspects about the different processes. Chapter 3 explains the assumptions and inputs of the supply chain model, and then reports its mathematical formulation. Finally, in Chapter 4 the results of the model are presented for different scenarios and in the end the conclusions of the Thesis are reported.

Chapter 1

Critical materials for renewable energy technologies

Chapter 1 provides an overview of the recent growth of green technologies in Europe. It specifically examines critical materials integral to these technologies and explores associated issues. This analysis aims to provide the motivation behind this thesis work. The chapter then delves into a detailed definition of these critical materials, along with an explanation of the data utilised in this research. The final section comprehensively outlines the objectives of the thesis.

1.1 Contextual Overview and Motivation: CRM Challenges in Clean Energy Transitions

In 2020, despite the disruptions caused by the pandemic, clean energy transitions gained traction. Renewable electricity saw record growth, and there are expectations for continued expansion in the coming years (IEA, 2020). Electric car sales surged by 40% in 2020, respect to the previous year, outpacing a sluggish global market (IEA, 2021). In recent years, numerous countries and leading companies have committed to achieving net-zero emissions by the mid-century, and new initiatives are born, such as the REPowerEU plan (EC, 2023b). After the Russian invasion of Ukraine, the European Union (EU) leaders outlined measures to rapidly reduce gas, oil, and coal reliance. Thus, in May 2022 they introduced the REPowerEU plan, focused on energy efficiency, clean energy production, and diversification of energy supplies for the European Union. It aligns with the goal of climate neutrality by 2050, in accordance with the European Green Deal. The plan emphasizes strategic autonomy and a resilient energy system for the EU (JRC, 2023). The increased focus on clean energy transitions underscores the importance of reliable supply chains, particularly for critical materials, which include, among others, minerals essential for various clean energy technologies. Indeed these ones, such as solar panels, lithium batteries and NdFeB permanent magnets from wind turbines and electric vehicles, that are discussed in this work, rely on specific minerals for their production. Ensuring an ample supply of critical materials is essential for sustaining these technologies and supporting the acceleration of energy transitions, however this represents a significant challenge. While energy security discussions have traditionally centered on oil, natural gas, and electricity, policymakers now need to enlarge their perspective to address potential new challenges as clean energy transitions progress (IEA, 2022b).

In general, many critical raw materials face significant concentration in their supply. For instance, China dominates the EU's REE supply, accounting for 98%. Turkey is the primary source for 98% of the EU's borate supply, while South Africa fulfills 71% of the EU's platinum needs and an even greater share of the platinum group metals, including iridium, rhodium, and ruthenium (EC, 2020). To better understand the global situation, a map with the shares of the different materials from the different countries is reported in Figure 1.1.

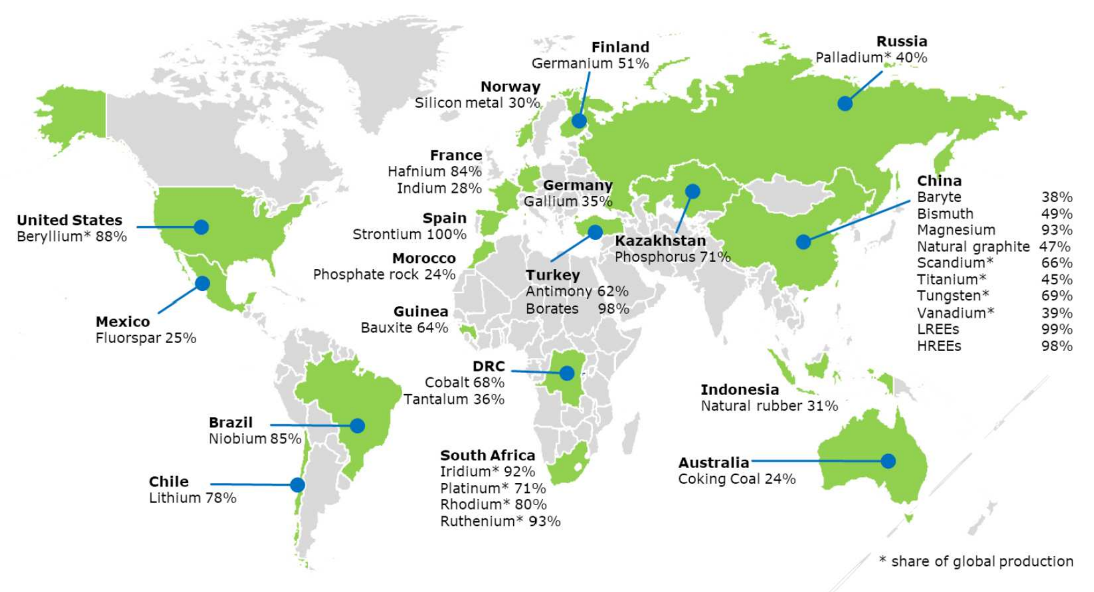

Figure 1.1. *Biggest supplier countries of CRMs to the EU (EC, 2020).*

These statistics confirm the need for the EU of an independent path to these critical materials. However, starting new projects in this context quickly is quite tough. The challenges include financial risks, lack of support for exploration, and lengthy government approval processes. Public resistance to mining activities in Europe also adds to the difficulties in getting these projects off the ground promptly (EC, 2020). Therefore a crucial role in this context will be played by recycling processes for the technologies containing these minerals. The European Union has increased in the last years the use of recycled critical raw materials, thanks to the European Green Deals Circular Economy Action Plan (EC, 2019). However a lot of sectors, especially green technologies or high-tech ones, keep facing difficulties for this purpose (EC, 2020). Considering the Italian situation, in particular regarding the three sectors analysed in this work (PV panels, EV lithium batteries and NdFeB magnets from EV and wind turbines), there are only few examples of recycling companies that are actually operative, and all of them are operating at small capacities. In the last years, different projects are starting to take place to the aim of recycling these technologies, in particular for photovoltaic panels and lithium batteries. For example, for the PV sector IREN (IREN, 2024) and Innovatec (Haiki Mines), together with V.E.R.I.T.A.S. and 9-Tech (HAIKI MINES (INNOVATEC)), presented two projects that will be operative respectively within 2024 and 2025. In the lithium batteries sector, there are different projects in the incubation phase, for example, the one proclamed by Enel X together with Midac and ENEA (EnelX, 2024), or Acrobat project of ENEA (2024). Another example in this field is the collaboration between Reinova and AC Ecotech (EnergiaMercato, 2023). These projects have been announced without specifications on the location that will be selected for the different recycling facilities. This study aims to model and analyse the potential of a hypothetical Italian supply chain dedicated to the recycling of critical materials. The focus is on implementing a variety of recycling plants tailored to green technologies such as photovoltaic panels, lithium batteries, and NdFeB magnets across Italy.

The objectives of this thesis will be more comprehensively elucidated in Section 1.4.

1.2 Definition of CRM

The CRM are defined as such based on the study performed by EC (2023c) in which 70 candidates are screened, 67 of which are individual ones, while three of them are groups: ten heavy (HREEs) and five light (LREEs) rare earth elements, and five platinum-group metals (PGMs). This results in a total of 87 individual raw materials.

The assessment is based on the values of two main parameters, namely the supply risk (SR) and the economic importance (EI), whose threshold values, if reached or exceeded, characterize a raw material as critical. In the EC Guidelines on the methodology for establishing the EU list of critical raw materials (EC, 2017) the definitions of these parameters, together with their calculation procedure, are thoroughly explained, while a brief summary is here reported.

1.2.1 The economic importance

The economic importance (EI) parameter aims to offer a comprehensive understanding of the relevance of a material within the EU economy. This assessment takes into account its usage in end-use applications and the value added (VA) within relevant EU manufacturing sectors at the NACE Rev.2. The refinement of economic importance involves the substitution index SI_{EI}, considering the technical and cost performance of available substitutes for specific applications. Mathematically, the economic importance is defined as:

$$EI = \sum_{s} (A_s \cdot Q_s) \cdot SI_{EI} \quad , \tag{1.1}$$

Where 'EI' represents economic importance, 'A_s' denotes the end use share of a material in a NACE Rev. 2 sector, 'Q_s' signifies the value added (VA) of the sector at the NACE Rev. 2, 'SI_{EI}' stands for the raw material substitution index (EI), and 's' represents the sector.

The Substitution index is calculated as:

$$SI_{EI} = \sum_{i} \sum_{a} SCP_{i,a} \cdot Sub - share_{i,a} \cdot Share_a \quad , \tag{1.2}$$

Where 'i' indicates a substitute material, 'a' denotes a candidate material individual end use, 'SCP' represents the parameter representing the substitute cost performance, Share signifies the raw materials share in an end-use employment, and Sub-share represents the substitutes sub-share within a specific application.

1.2.2 The supply risk

The SR parameter measures the susceptibility of the European Union's material supply chain to potential disruptions by evaluating the primary supply from nations involved in raw materials production. This assessment considers the governance standards and trade dynamics of these countries. SR specifically targets the critical stage in the material supply chain, often the bottleneck involving extraction or processing, which poses the greatest risk to the EU's supply stability. The evaluation also factors in strategies such as substitution and recycling as methods to alleviate and handle supply risks. It quantifies the vulnerabilities and potential impacts on the EU's material supply chain:

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU sourcing} \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR} \quad . \tag{1.3}$$

Where 'SR' denotes supply risk, 'GS' stands for global supply, '$EU_{sourcing}$' represents actual sourcing of the EU supply, which involves both domestic production within EU member countries and the importation of goods from other nations, 'HHI' signifies the Herfindahl-Hirschman Index representing country concentration, 'WGI' indicates the scaled World Governance Index representing country governance, 't' is the trade parameter used to regulate WGI, 'IR' stands for import reliance, 'EoL_{RIR}' represents the recycling input rate for end-of-life equipment, and 'SI_{SR}' denotes the substitution index for supply risk.

The import reliance and $HHI_{WGI,t}$ are instead calculated as:

$$IR = \frac{IM - EX}{DP + IM - EX} \quad , \tag{1.4}$$

$$(HHI_{WGI,t})_{GS\ or\ EU sourcing} = \sum_c (S_c)^2 WGI_c \cdot t_c \quad , \tag{1.5}$$

Where 'IM' stands for import, 'EX' for export and 'DP' for domestic production. 'S_c' represents the share of the raw material for country c, 'WGI_c' denotes the scaled World Governance Index for country c, and it includes types of export restrictions.

Variable t_c is constructed as:

$$t_c = (ET - TA_c\ or EQ_c\ or EP_c\ or EU_c) \quad , \tag{1.6}$$

Where 't_c' represents the trade-related variable of country c for a candidate raw material, 'ET-TA_c' denotes the parameter reflecting an export tax imposed (%) by country c, possibly mitigated by a trade agreement in force, 'EQ_c' is the parameter reflecting an export physical quota imposed by country c (physical units, e.g., tonnes), 'EP_c' represents the parameter reflecting an export prohibition introduced by country c for a candidate raw material, and 'EU_c' stands for the parameter of EU countries c

for a candidate, equal to 0.8.

The end-of-life recycling input rate (EOL_{RIR}) indicates the percentage of recycled material derived from old scrap relative to the overall European demand for a specific raw material, and it is defined as:

$$EOL_{RIR} = \frac{IN_{SM}}{IN_{SM} + IN_{PM}} \quad . \tag{1.7}$$

Where IN_{SM} represents the input of secondary material to EU from old scrap, while IN_{PM} represents the input of primary material to EU. The supply risk substitution index (SI_{SR}) is defined as:

$$SI_{SR} = \sum_i [(SP_i \cdot SCr_i \cdot SCo_i)^{1/3} \cdot \sum_a (Sub - share_{i,a} \cdot Share_a)] \quad , \tag{1.8}$$

Where 'i' indicates a substitute material, 'a' indicates an employment of the raw material, '*SP*' represents substitute production, an indicator considering the global production of both the substitute and the material in question, aiming to determine if there are ample quantities of substitute material available on a global scale. '*SCr*' denotes the criticality of the substitute, taking into account if the substitute was listed in the previous EU list of critical materials. '*SCo*' stands for the co-production of the substitute, considering if the substitute is mined as a co- or by-product or if it's a primary one. '*Share*' represents the candidate material's share in an end-use employment, and '*Sub-share*' denotes the substitute sub-share in each application.

1.2.3 CRM final list

The calculation procedure of the different parameters is reported in detail in EC (2017). The threshold values of the two different factors are fixed at 1.0 for the supply risk and 2.8 for the economic importance, rounded to one decimal. Therefore it can be concluded that a raw material is considered as critical if at the same time $SR \geq 1.0$ and $EI \geq 2.8$ (EC, 2023c). In Figures 1.2 and 1.1 are reported the results of the EU criticality assessment and the 2023 updated list of CRM (EC, 2023c).

This list is updated each year by the European Commission (EC), and in 2023, 34 Critical Raw Materials have been recognised. Copper and Nickel are not critical, since their supply risk is lower than one, however they are reported in the list as strategic raw materials. Strategic materials help in making Europe more independent in the manufacturing of tactical products and services, such as green energy, digital technology and defense; they are defined based on different parameters, namely strategic importance

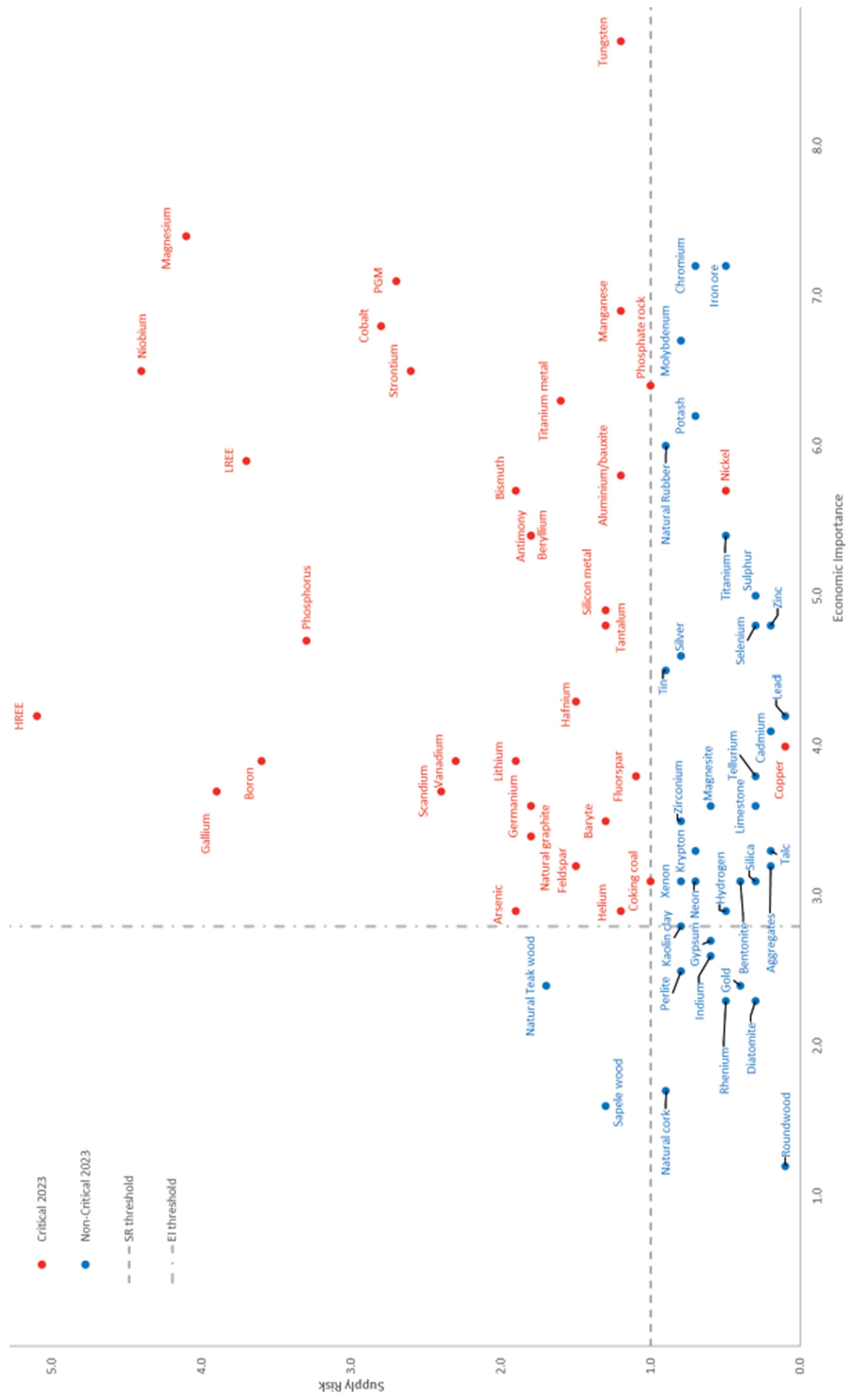

Figure 1.2. *Results of the 2023 EU criticality assessment (EC, 2023c).*

Table 1.1. *List of the EU 2023 CRM (EC, 2023c).*

2023 Critical Raw Materials (New CRM in italics)			
aluminium/bauxite	coking coal	lithium	phosphorus
antimony	*feldspar*	LREE	scandium
arsenic	fluorspar	magnesium	silicon metal
baryte	gallium	*manganese*	strontium
beryllium	germanium	natural graphite	tantalum
bismuth	hafnium	niobium	titanium metal
boron/borate	*helium*	PGM	tungsten
cobalt	HREE	phosphate rock	vanadium
		*copper**	*nickel**

in the different sectors, forecast demand growth and difficulty of increasing production ((EC, 2023a)).

1.3 CRM data

From the resulting 34 critical or strategic materials, the ones contained in the three technologies considered in this study, namely photovoltaic panels, lithium batteries and NdFeB magnets, were analysed. In particular the focus is on the materials that, for each technology, can be recycled with the different technologies that are reported in Chapter 2. The list of materials is reported in Table 1.2.

Table 1.2. *Analysed CRM for the different technologies.*

Technology	**Element**
Photovoltaic panels	Al
	Cu
	Si
EV lithium batteries	Al
	Co
	Cu
	Li
	Mn
	Ni
EV and wind turbines NdFeB magets	Dy
	Nd
	Pr

1.3.1 Availability of green technology waste equipment in Italy

As detailed in Chapter 1.1, a supply chain analysis of these materials, involving the optimisation of both location and capacity for various recycling facilities, is conducted across Italy. To initiate this process, the total count of pieces for each distinct technology is determined within every Italian province as of the conclusion of 2021 (ANFIA, 2021; Wikipedia, 2023; GSE, 2021). In this thesis work, different scenarios have been analysed. Initially, a steady situation is assumed for the following years, until 2031. Therefore, considering the average lifetime of each technology, the total number of waste equipment for each province in a determinate year is obtained. Hence in the case of lithium batteries and permanent magnets of EVs, since the average lifespan can be considered around 10 years (ANL, 2019), the number of waste vehicles present for each province in year 2031 is estimated as 10% of the 2021 value. Then, considering that 2 kg of permanent magnets are present in each electric vehicle (N.-E. Menad, 2016), and that the average weight of an EV lithium battery is 330 kg (Grunditz and Thiringer, 2016) the total mass of waste batteries and magnets from electric cars in 2031 are obtained. For photovoltaic panels the average estimated lifetime is about 25 years (Cui et al., 2022), while for wind turbines this turns out to be around 20 years (Delaney et al., 2023). Then, again the total mass of waste solar panels and magnets from wind turbines are estimated, knowing that 600 kg of magnets are needed to generate 1 MW of wind power (N.-E. Menad, 2016), while the power/weight ratio for an average photovoltaic panel is 0.013 kW/kg (Cui et al., 2022). After that, for each technology, the different quantities of critical materials are calculated, according to the compositions reported in Table 1.3.

Table 1.3. *Critical material composition of the different technologies.*

Technology	Element	Weight %
Photovoltaic panels	Al	8
	Cu	1
	Si	3.6
EV Lithium batteries	Al	15
	Co	7
	Cu	10
	Li	7
	Mn	5
	Ni	4
EV and wind turbines NdFeB magets	Dy	0.45
	Nd	25.32
	Pr	3.1

After that, the 2050 situation has been analysed, leveraging the forecasts performed in IEA (2023b) for the different technologies. Thus, starting from the 2031 situation, Eq.(1.9) is used to calculate the availability values of waste equipment for each technology in 2050:

$$Value_{2050} = Value_{2030} \cdot (CAAGR + 1)^t \quad . \tag{1.9}$$

Where CAAGR stands for compound average annual growth rate and t reflects the considered time period, in years. In IEA (2023b) three different scenarios are analysed, namely the stated policies scenario (STEPS), the announced pledges scenario (APS) and the net zero emissions by 2050 scenario (NZE). IEA (2023b) does not provide specific data on the compound average annual growth rate for electric vehicles. However, it does present growth values for battery storage across the different scenarios. Therefore, for the purposes of this thesis, it is assumed that the growth of the electric vehicle market mirrors that of the battery market. In table 1.4 the CAAGR values from 2030 to 2050 for the different scenarios and for the different technologies are reported.

Table 1.4. *CAAGR values for different green technologies for different scenarios (IEA, 2023b).*

CAAGR %			
Technology	STEPS	APS	NZE
PV	5.7	7.08	7.1
WIND	4.04	5.65	6.25
EV	7.5	7.57	7.34

The three scenarios are exhaustively described in IEA (2023b), while here a brief introduction is reported in order to understand their meaning:

- NZE: this normative scenario represents a strategic trajectory for the energy sector aimed at mitigating the global temperature rise to 1.5 °C above pre-industrial levels by the year 2100. This objective is pursued with the intention of achieving at least a 50% probability of success, all while minimising the extent of overshooting this temperature threshold.

- APS: in this scenario, it is assumed that governments will successfully fulfill all their climate-related commitments, encompassing both short-term and longer-term goals. These commitments extend beyond climate-specific targets to include broader areas like enhancing energy access. As a result, the scenario, is associated with temperature rise of 1.7 °C by the year 2100, with a 50% probability.

- STEPS: this scenario serves as an empirical evaluation of the energy sector's trajectory. In contrast to the APS, which relies on governments' stated commitments, the STEPS examines the tangible measures governments are actively undertaking to realise their energy objectives. Presently, the STEPS is correlated with a projected temperature increase of 2.4 °C by 2100, with a 50% probability.

1.3.2 Italian demand of CRM

A demand estimation for the critical materials under consideration have been carried out. This analysis relies on data extracted from the foresight report on raw materials and strategic supply chains, provided by the EC (JRC, 2023). The database, reported in Chapter 4, presents critical material quantities within various renewable technologies across different scenarios and years. Specifically, it provides demand data for the years 2020, 2030, and 2050, taking into account two distinct scenarios. The first one, namely the Low Demand Scenario (LDS) is characterized by gradual technology deployment and various combinations of market shares and material intensities. This results in a relatively moderate increase in materials demand and, in some cases, even a decrease. However, the overall growth pattern is evident. For example, in the LDS, the projected 2050 global demand for lithium and graphite is approximately 14 and 7 times the current global supply, respectively, while for dysprosium and neodymium, it is around 1.5 times (JRC, 2023). In contrast, the high demand scenario (HDS), pictures a prompt deployment of technology and a blend of market shares and material intensities, leading to a significant rise in materials demand. In essence, this scenario aligns with the ambitious energy and climate change mitigation goals set by the different countries. The forecast obtained from the EC contains the European and global material demand for different technologies. This work is based on the Italian territory, and thus these data need to be scaled. The selected scaling criteria is based on the population ratio between EU and Italy (ISTAT, 2023; EUROSTAT, 2023).

1.4 Thesis motivation and objectives

In the context described in this chapter, the primary goal of the thesis is to formulate a supply chain framework for CRM. This supply chain model is specifically designed to the Italian distribution network of various technologies, including lithium batteries from EV, PV panels, and Nd-FeB magnets from wind turbines and EV. The objective is to optimise the placement of potential recycling facilities across Italy.

The proposed model is designed to minimise overall costs incurred throughout the supply chain, particularly focusing on transportation from collection points to recycling plants and the capital and operational expenses of these plants. The key decision variables include determining the optimal locations and capacities for recycling plants for each technology, as well as optimising the material flow distribution.

These findings offer valuable insights for selecting suitable locations for recycling plants tailored to specific technologies.
Moreover, the quantities of critical materials obtained from recycling the different technologies, can be compared with the demand estimate for the year 2030. This comparison is important because highlights the differences between the recycled CRM and the ones required for the development of green technologies in the future. If the discrepancy between the two proves to be significant, it will reflect a strong Italian dependence on CM import form other countries, revealing also that recycling alone cannot sustain the thorough requirements. Even in this case, the analysis can result useful to understand the impact of recycling on the CRM demand fulfillment and thus on the journey to the net zero emissions by 2050. Therefore, summarising, the objectives of this thesis are:

- Analysing the state of art of the different recycling processes for photovoltaic panels, lithium batteries and permanent NdFeB magnets of wind turbines and electric vehicle, considering both technological and economic aspects;

- Proposing a mixed integer linear programming model for the economic optimisation of the supply chain for critical raw materials at the Italian level. The modeling framework includes photovoltaic panels, lithium batteries from EV, NdFeB permanent magnets from EV and wind turbines;

- Comparing the CM quantities obtained from recycling processes, and the ones estimated by the European forecasts;

- Investigating different scenarios, based on the future developments of the different national and European policies.

The operative procedure begins by considering the waste equipment available in different Italian provinces. Subsequently, the transportation of these technologies to recycling plants, either by truck or ship, is meticulously modelled, taking associated costs into account. An economic optimisation is then conducted to identify the optimal locations for these recycling plants, along with the optimal material flow distribution and transportation mode. These optimal locations are determined by minimising the total costs, encompassing both transport and plant-related expenses.

The ultimate objective of this study is to provide essential insights for strategically selecting the most favorable locations for diverse recycling facilities anticipated to be established in the coming years.

Chapter 2

Recycle technologies for critical materials

Chapter 2 provides a literature review concerning the recycling processes employed for the various green technologies examined in this thesis, namely, photovoltaic panels, EV lithium batteries and permanent NdFeB magnets from EV and wind turbines.

2.1 Photovoltaic panels

2.1.1 State of art

Photovoltaic (PV) technology has emerged as a prominent player in the global renewable energy landscape over the past decade. Among various PV technologies, crystalline-silicon PV remains the predominant choice, commanding an 85-90% share of the market (IEA, 2014). With the substantial existing installations of PV panels and anticipated growth, the volume of discarded PV panels is projected to reach 9.57 million tonnes by 2050 (BioIS, 2011). Managing the recycling of waste PV panels poses a significant challenge for future waste treatment facilities. The complexities associated with end-of-life (EoL) management, including plant dismantling, collection, and transport, are expected to escalate, particularly given the widespread and diverse distribution of panels at an urban scale (Cellura et al., 2012). The initial exploration of the technical and economic viability of recycling crystalline PV modules was already introduced in a photovoltaic technology conference in the 1990s (Latunussa et al., 2016).

However, genuine interest in PV recycling gained momentum approximately a decade later. For instance, Fthenakis (2000) conducted a study outlining the challenges and potential approaches for PV recycling in the USA. The conclusion was that PV recycling is both technologically and economically feasible, despite requiring careful consideration and planning. After these initial studies, a lot of different researchers focused their work on this topic, proposing multiple types of processes (Doi et al., 2001; Frisson et al., 2000; Zeng et al., 2004; Granata et al., 2014; Klugmann-Radziemska and Ostrowski, 2010; Wang et al., 2012; Kang et al., 2012).

These technical methods introduced so far are based on chemical, physical or chemical-physical treatments. In this thesis, the analysed process is the "full recovery end of life photovoltaic project" (FRELP) method, specifically focusing on the recycling of crystalline silicone (c-Si) panels. The FRELP approach has effectively addressed each stage of the c-Si photovoltaic treatment process, successfully implementing technological solutions. This has resulted in the development of a technically and economically viable industrial process design based on the retrieved information (Latunussa et al., 2016).

2.1.2 FRELP recycling process

In the recycling technologies used in the last years, through the use of mechanical disposal processes, only some of the components of the disposed panels are fully valorised. Furthermore, if not disposed of properly, the waste panels can cause both environmental and human health problems. Therefore, the floor remains open for the development of new sustainable solutions for PV panel recovery. It is expected that starting from 2015, over the next 20 years 500000 t/year of panels will be disposed in Europe, of which:

- 390000 t/year of glass;
- 55000 t/year of aluminum;
- 35000 t/year of plastics;
- 11500 t/year of crystalline silicon cells (SASIL, 2023).

Most of current technologies recycle low-value glass, such as fiberglass or for insulation. Moreover, they do not allow the recovery of metals, particularly crystalline silicon, which is used in more than 90 percent of the world's PV cells. The production of silicon involves high energy costs, which is a serious drawback in terms of environmental performance in view of a life-cycle approach.

In this context, the FRELP project aims to test and develop innovative technologies to recover 100 percent of end-of-life photovoltaic panels in an economically sustainable way. Two main environmental solutions are proposed:

- the recovery of extra-clear, high-quality glass for use in the glass industry hollow and flat glass, very significantly reducing both the consumption of energy and CO_2 emissions in the glass melting process;
- the recovery of silicon metal, to be used as ferro silicon in ferrosilicon alloys or, if pure enough, transformed into amorphous silicon for the production of thin films, greatly reducing energy consumption and CO_2 emissions associated with primary silicon production.

2.1.3 PV panels recycling process description

The thorough description of the FRELP recycling process is reported in (Latunussa et al., 2016), while a brief summary is here reported. The waste panels arrive to the recycling facility, then they are loaded on a conveyor belt that brings them to the dismantling phase. A Cartesian robot is used to supply the panels to the dismantling part, where the edges of the aluminium frame are cut, and the remaining part of the frame is shredded. Then, in the next section, the cables are detached from waste panels and sent to a separate facility for further treatment. The plastic components separated from the cable mass are sent to an incineration plant integrated with an efficient energy recovery system. The aluminium frame is, instead, collected. The PV waste without the frame and the cables is sent to the next section, where the glass layer is separated from the rest of the panel. Heat provided by infra-red radiation is used in order to facilitate the mechanical detaching of the glass. At the end of this section, the glass pieces are collected and brought to a separate section dedicated to glass refinement. Here, the glass pieces are sieved in order to separate the pieces of different sizes. Then, by means of an optical-based inspection device, the glass pieces that contain impurities are isolated and disposed of. After removing the glass layer, the remaining part of the panel is composed of layers of polymers and cells, often called 'PV sandwich'. The latter is cut in pieces of smaller sizes, and transported to an incinerating facility, where a residual bottom ash containing silicon and other metals is obtained. Also, a fly ash is obtained, which must be appropriately disposed of, being an hazardous waste. The bottom ash needs to be sieved to recover the residual aluminium connector. Then, it undergoes an acid leaching process, in which a solution of water and nitric acid (HNO_3) is used to dissolve the metals, leaving silicon metal in the residue. The acid solution is then treated by electrolysis, which allows the recovery of silver and copper. Then, the acid solution, with the residue of electrolysis is neutralised by means of calcium hydroxide. After that, a filter press divides the liquid waste, mainly composed by calcium hydroxide and water from a residual sludge. Both the sludge and the liquid waste need to be transported to adequate landfills. The different steps of the process are represented in figure 2.1.

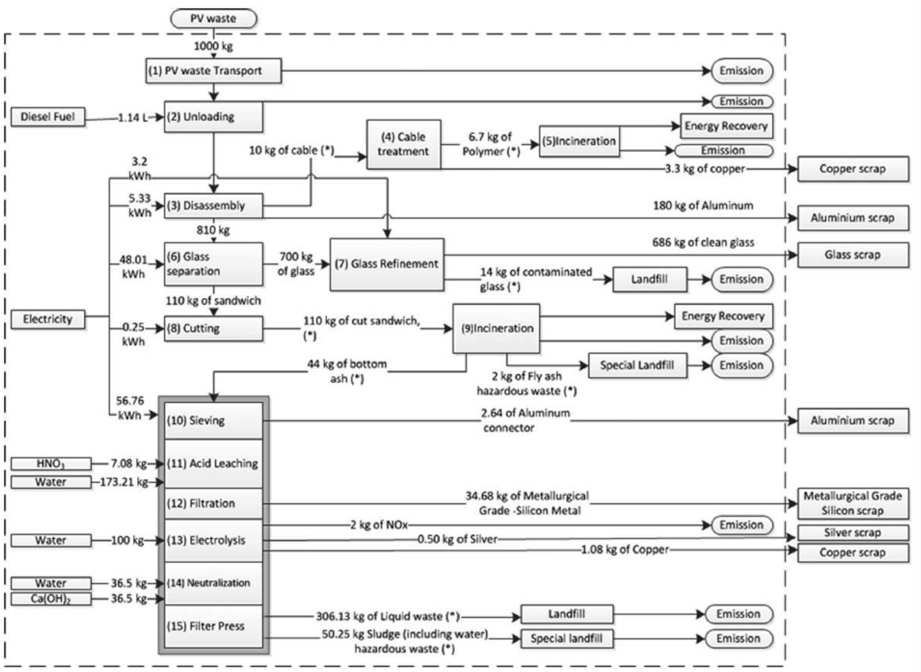

Figure 2.1. *Different steps of the recycling process for waste photovoltaic panels (Latunussa et al., 2016)*

The techno-economical data needed for the optimisation is instead retrieved from Cui et al. (2022), in which the different costs of the FRELP process are reported.

2.2 Rare earth permanent magnets

2.2.1 State of art and general assumptions

The global situation regarding NdFeB magnets recycling is still in a premature phase. In Europe, there have been few projects developed in the last few years on this topic.

However, thus far, there are mainly laboratory-scale or pilot plants installed for this purpose, with few industrial-scale ones announced for the next few years. For example, an innovative company, HyProMag, dedicated to NdFeB magnets recycling, is starting new projects, namely short loop recycling plants at Tyseley Energy Park in Birmingham, UK and other locations (HYPROMAG, 2023). Other projects, financed by the EU, and in particular under the frame of Horizon 2020, that are dedicated to rare earth magnets recycling, are REMANENCE (2023), REProMag (2023), SUSMAGPRO (2023), SecREEts (2023), EREAN (2023), REEcover (2023) and REE4EU (2023). In the literature, there is a lack of scientific papers or reports on the techno-economic analysis of hypothetical magnet recycling processes. However, Chowdhury et al. (2021) conducted a cost estimate for a potential process of recycling NdFeB magnet swarf. This swarf is a waste of magnet production, and it varies in quantity depending on the complexity of the final magnet shape. As it is only generated in the final stages of production, such as cutting and shredding, its chemical composition is assumed to be similar to that of the final magnets. Additionally, the recycling process described by Chowdhury et al. (2021) resembles other processes reported in the literature. Therefore, the information reported in Chowdhury et al. (2021) is exploited to accomplish the purpose of this thesis work.

2.2.2 NdFeB magnets recycling process description

The exhaustive description of this recycling process is reported in Chowdhury et al. (2021), while a brief explanation is here reported. The magnet swarf, with a considered REE content of 31%, is first dissolved in a continuously stirred reactor with a solution of copper nitrate hemi(pentahydrate) salt. The reaction in exothermic, and this step is carried out in about 5.5 h. The result is a solution that contains the rare earth elements, namely neodymium, dysprosium and praseodymium, together with copper and iron precipitates, that are filtered out in order to achieve a REE solution with higher concentration. Subsequently, oxalic acid is introduced to generate rare-earth oxalate. Although iron-ammonium oxalate precipitates concurrently, it exhibits high solubility in water. Therefore, hot water is incorporated during the next filtration stage to dissolve and eliminate impurities from the rare-earth oxalate. After the filtration step, the rare-earth oxalate is calcined at a temperature of 800 °C, producing a REOs mixture with a purity higher than 99.5%. Within this procedure, wastewater is generated, and its treatment involves the application of a combination of calcium chloride and hydroxide to eliminate iron. Subsequently, the treated wastewater undergoes filtration, yielding a solution containing ammonium chloride and nitrate, suitable for agricultural applications following further processing. The copper salts that are obtained in the first steps, are recovered in order to be reused in the process. Extractive pyrometallurgy or hydrometallurgical processes need to be implemented in order to recover metallic copper from the mixture of impurities collected in the first filtration step. Following the hydrometallurgical method, copper and Cu_2O are oxidised into CuO at ambient conditions. Then, to remove iron oxides, the obtained mixture is treated with $KHSO_4$. Subsequently, calcium nitrate is added into the mixture to turn copper sulfate, formed after the addition of $KHSO_4$, in copper nitrate. Thus, the obtained copper nitrate can be recycled back to the initial part of the process, for the acid-free dissolution. The recycling rate achieved for copper nitrate, in this case, is about 70%. Potassium nitrate is generated after the addition of $KHSO_4$, but it is reintroduced in the first step of the process with the copper nitrate, without introducing noticeable changes. The process flow diagram is reported in figure 2.2, that is relative to a plant which recovers 32 metric tons of REOs from 100 metric tons of NdFeB magnets swarf (Chowdhury et al., 2021).

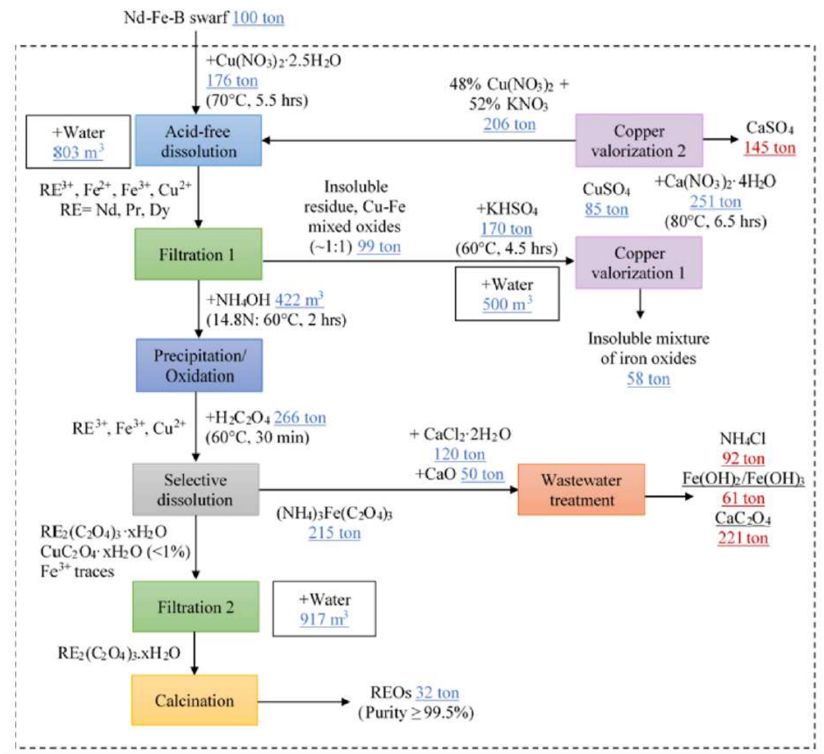

Figure 2.2. *NdFeB magnets swarf recycling process (Chowdhury et al., 2021).*

2.3 Lithium batteries

2.3.1 State of art

The recycling of lithium batteries has become a critical aspect of sustainable resource management, driven by the increasing usage of lithium-ion batteries for electric vehicles, and different recycling technologies have been developed in the last years. Several companies have emerged as leaders in the field, employing advanced technologies to recover valuable materials and minimise environmental impact. The different ways developed by some of the most important companies in the field are depicted in figure 2.3. Akkuser is a company that receives all the spent portable batteries collected in Finland, recognised for its innovative approaches to lithium battery recycling (Akkuser, 2023). The company exploits two different steps of comminution, and a magnetic separation to recycle the battery components. A pyrometallurgical process is used for plastic parts, in order to exploit the chemical energy contained in plastics by burning them. Umicore is a global player in materials technology and recycling, with a significant focus on lithium battery recycling. The company aims to create sustainable solutions for the entire battery life cycle (Umicore, 2023). Umicore employs a combination of pyrometallurgical and hydrometallurgical processes, to recover most of the metals from spent batteries. The batteries are directly burnt without disassembling them: an alloy is obtained, from which cobalt, nickel, copper and iron are recovered through to a hydrometallurgical step. Also a slag containing lithium is obtained, from which this element can be recovered again by an hydrometallurgical step, even though this is not done by the company, due to the high costs of this technique. Again in this case plastics and electrolytes are burnt to reduce the energy consumption of the process. Recupyl (Recupyl, 2023) is a French company known for its expertise in developing environmentally friendly processes for battery recycling. The company is committed to maximising the recovery of critical materials while minimising environmental impact. Recupyl employs a combination of advanced separation steps and an hydrometallurgical extraction process. Retriev is an American company specialized in end-of-life battery management and recycling solutions. The company employs advanced size separation steps, together with a dry thermal process and a froth flotation step to recover valuable materials and ensure proper disposal of hazardous components. Duesenfeld is another global player in the recycling industry, providing comprehensive solutions for various waste streams, including lithium batteries (Duesenfeld, 2023). Duesenfeld utilizes vacuum dying techniques, together with magnetic and density separation and hydrometallurgy, to extract and refine metals from batteries.

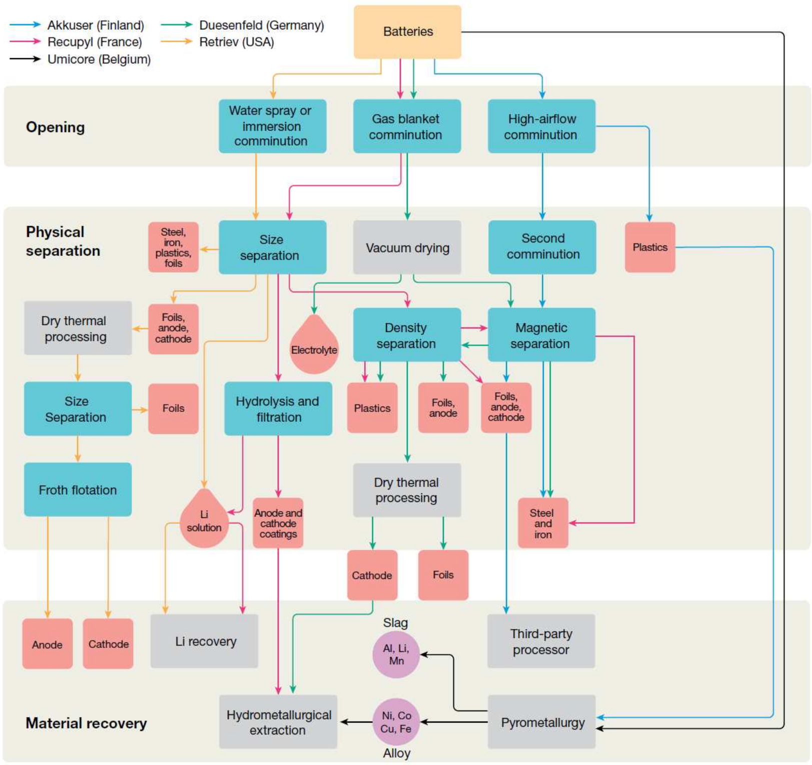

Figure 2.3. *Different routes employed for battery recycling and materials recovery (Harper et al., 2019).*

In conclusion, the state of the art in lithium battery recycling involves a combination of innovative technologies, mainly based on pyrometallurgical and hydrometallurgical processes.

2.3.2 EverBatt model and EV lithium batteries recycling process description

Given the considerable increase in the use of electric vehicles in recent years, and in order to help stakeholders better understand the costs and environmental benefits of recycling lithium batteries, Argonne National Laboratory created the EverBatt model. It is a model open to the public and it focuses on both the economic and environmental aspects of closed-loop battery recycling. Supported by the Department of Energy, EverBatt is a useful tool for evaluating different recycling technologies, figuring out research and development needs, and tackling challenges in the field (ANL, 2019). In this thesis work, this model is utilised to determine the recycling costs for lithium batteries, which will be incorporated into the supply chain model. EverBatt allows the selection of the desired technology for battery recycling, to estimate the associated environmental and economic impacts. The available technologies considered by the model are pyrometallurgy, hydrometallurgy and direct recycling. In this thesis the selected route is the hydrometallurgical one, since, with respect to pyrometallurgy, it allows the recovery of Lithium and the other critical materials, without the need of further treatments. Moreover, with respect to the direct recycling route, the hydrometallurgical one results to be more established in the specific literature. Figure 2.4 illustrates the comprehensive process flow of a generic hydrometallurgical recycling method. The initial

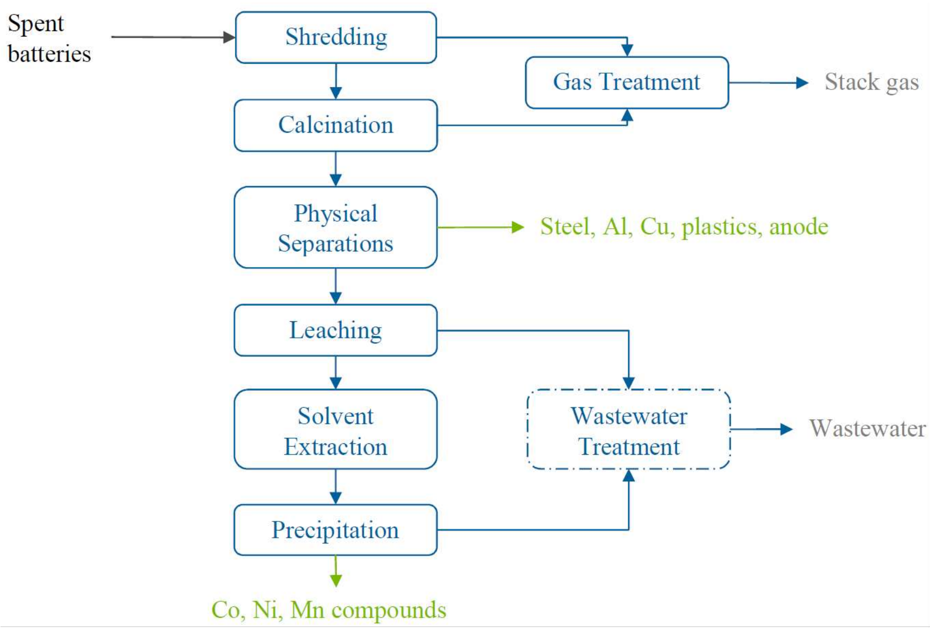

Figure 2.4. *Process diagram of a generic hydrometallurgical recycling process (ANL, 2019).*

step involves the shredding of discharged and disassembled spent batteries, followed by subjecting them to a low-temperature calcination process designed to eliminate the binder and electrolyte components. The subsequent stages include various physical separation processes aimed at segregating aluminum, copper, steel into metal scraps, and plastics. A leaching process is then initiated, complemented by solvent extraction and, at times, precipitation techniques to generate Co/Ni/Mn compounds. Additionally, there exists the potential to produce lithium carbonate, a crucial component for the manufacture of new cathode materials.

2.4 Recovery of the different CRM

For each of the different recycling technologies, there is a specific recovery value for each recovered critical material, as reported in Table 2.1. Considering these recovery

Table 2.1. *Recovery values for the different critical materials in the analysed recycling processes (BATT stands for lithium batteries, and MAG for NdFeB magnets)*

	Element	Recovery	Ref.
PV	Al	0.994	(Cui et al., 2022)
	Cu	0.970	
	Si	0.970	
BATT	Al	0.900	(ANL, 2019)
	Co	0.980	
	Cu	0.900	
	Li	0.900	
	Mn	0.980	
	Ni	0.980	
MAG	Dy	0.970	(Chowdhury et al., 2021)
	Nd	0.970	
	Pr	0.970	

values, input and output data can be derived based on the availability of waste equipment in each province, as well as for the entire country.

Chapter 3

Supply chain model

Chapter 3 describes the assumptions, input data, and mathematical formulation of the presented supply chain model. The objective of the model is to find the optimal supply chain for CRM recycling in Italy, taking into account two primary modes of transportation: truck and ship transport.

3.1 Model assumptions and inputs

The modelled supply chain focuses on critical materials for different green technologies, namely photovoltaic panels, EV lithium batteries and NdFeB magnets from EV and wind turbines, as introduced in Chapter 1. The supply chain is schematically depicted in Figure 3.1, illustrating its main stages.

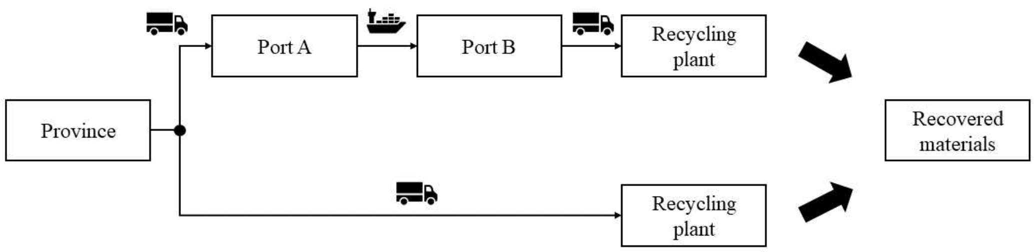

Figure 3.1. *Block diagram of the modelled supply chain.*

Initially, waste materials from each technology are gathered at designated points within each province, typically at the provincial capital. This results in one node being allocated to each province in the model, aligning with its capital city, resulting in a total number of 123 nodes. Table 3.1 further details the geographic coordinates, in radians, of each capital city together with the specific quantities of waste material available at each node, for the base case scenario. Data for the other scenarios are reported in the Appendix 4.4.

Table 3.1. *Coordinates and availability of waste materials for each province [t/year].*

	Lat [rad]	Long [rad]	Total PV	Total BATT	Total MAG
Alessandria	0.784	0.150	858	18	0.11
Asti	0.784	0.143	297	9	0.06
Biella	0.795	0.141	302	8	0.05
Cuneo	0.775	0.132	1853	37	0.54
Novara	0.793	0.150	358	22	0.14
Torino	0.787	0.134	1489	174	1.05
Verbania	0.802	0.149	65	8	0.05
Vercelli	0.791	0.147	291	9	0.06
Aosta	0.798	0.128	81	54	0.39
Bergamo	0.798	0.169	1129	88	0.54
Brescia	0.795	0.178	1715	111	0.68
Como	0.800	0.159	346	57	0.35
Cremona	0.788	0.175	809	24	0.14
Lecco	0.800	0.164	190	29	0.18
Lodi	0.791	0.166	425	12	0.08
Mantova	0.788	0.188	792	25	0.15
Milano	0.794	0.160	1208	248	1.50
MonzaBrianza	0.796	0.162	394	69	0.42
Pavia	0.789	0.160	628	24	0.14
Sondrio	0.806	0.172	177	13	0.08
Varese	0.800	0.154	531	72	0.44
Bolzano	0.812	0.198	825	146	0.89
Trento	0.804	0.194	638	622	3.77
Belluno	0.805	0.213	163	7	0.04
Padova	0.792	0.207	1228	67	0.41
Rovigo	0.787	0.206	1021	8	0.05
Treviso	0.797	0.214	1238	65	0.40
Venezia	0.793	0.215	719	44	0.27
Verona	0.793	0.192	1325	81	0.72
Vicenza	0.795	0.202	1088	75	0.45
Gorizia	0.802	0.238	140	7	0.04
Pordenone	0.802	0.221	564	17	0.10

Trieste	0.797	0.240	98	10	0.06
Udine	0.804	0.231	1017	39	0.23
Genova	0.775	0.156	101	28	0.25
Imperia	0.766	0.140	94	6	0.04
LaSpezia	0.770	0.172	86	10	0.06
Savona	0.773	0.148	108	9	0.18
Bologna	0.777	0.198	1172	71	0.84
Ferrara	0.783	0.203	643	12	0.07
Forli	0.772	0.210	764	19	0.12
Modena	0.779	0.191	939	45	0.28
Parma	0.782	0.180	664	24	0.77
Piacenza	0.786	0.169	630	13	0.08
Ravenna	0.775	0.213	1253	22	0.13
ReggioEmilia	0.780	0.186	601	38	0.23
Rimini	0.769	0.219	318	17	0.10
Arezzo	0.759	0.207	561	13	0.12
Firenze	0.764	0.196	392	241	1.80
Grosseto	0.747	0.194	270	6	0.54
Livorno	0.760	0.180	254	10	1.95
Lucca	0.765	0.184	239	19	0.12
MassaCarrara	0.769	0.177	86	7	0.29
Pisa	0.763	0.182	336	17	2.90
Pistoia	0.767	0.191	145	12	0.07
Prato	0.766	0.194	261	11	0.07
Siena	0.756	0.198	250	10	0.06
Perugia	0.752	0.216	1151	28	0.21
Terni	0.743	0.221	427	7	0.04
Ancona	0.761	0.236	986	21	0.13
AscoliPiceno	0.748	0.237	393	10	0.06
Fermo	0.753	0.239	346	7	0.04
Macerata	0.756	0.235	994	14	0.34
PesaroUrbino	0.766	0.225	818	17	0.73
Frosinone	0.727	0.233	588	15	0.72
Latina	0.724	0.225	845	20	0.12
Rieti	0.740	0.224	93	4	0.03
Roma	0.731	0.218	1582	357	2.16
Viterbo	0.740	0.211	1496	10	1.11
Chieti	0.739	0.247	748	11	2.67
LAquila	0.739	0.234	544	10	1.03
Pescara	0.741	0.248	297	12	0.15
Teramo	0.745	0.239	793	11	0.07

Campobasso	0.725	0.256	427	4	6.47
Isernia	0.726	0.249	129	1	2.18
Avellino	0.714	0.258	292	7	3.74
Benevento	0.718	0.258	220	5	3.13
Caserta	0.717	0.250	865	20	0.62
Napoli	0.713	0.249	609	39	0.24
Salerno	0.710	0.258	857	26	1.27
Bari	0.718	0.294	1642	30	0.18
Barletta	0.721	0.284	552	5	0.83
Brindisi	0.709	0.313	1554	7	0.54
Foggia	0.724	0.271	1933	6	3.91
Lecce	0.704	0.317	2210	18	1.03
Taranto	0.706	0.301	1180	10	0.81
Matera	0.710	0.290	584	5	1.47
Potenza	0.709	0.276	611	7	2.77
Catanzaro	0.679	0.290	447	7	2.59
Cosenza	0.686	0.284	814	14	1.18
Crotone	0.682	0.299	124	1	6.21
ReggioCalabria	0.665	0.273	243	7	0.04
ViboValentia	0.675	0.281	135	2	0.01
Agrigento	0.651	0.237	729	4	2.65
Caltanissetta	0.654	0.245	306	3	0.02
Catania	0.655	0.263	766	31	0.19
Enna	0.656	0.249	239	2	2.44
Messina	0.667	0.271	238	12	0.08
Palermo	0.665	0.233	598	22	7.88
Ragusa	0.644	0.257	696	11	0.06
Siracusa	0.647	0.267	658	11	1.87
Trapani	0.664	0.218	513	7	1.59
Cagliari	0.684	0.159	780	20	1.87
Nuoro	0.704	0.163	455	6	3.09
Oristano	0.696	0.150	445	4	1.25
Sassari	0.711	0.149	768	16	8.42
SudSardegna	0.684	0.149	633	8	2.84
Total			**69521**	**3895**	**109**

Moreover, each capital city's location serves as a potential site for the installation of a recycling plant tailored to each technology. The next stage of the supply chain entails transporting the waste material from each province to the optimal location selected for recycling plant installation. The model includes two transportation modes: road transport utilising heavy-duty trucks and sea transport via barges.

A map of the Italian provinces and main ports is, instead, depicted in Figure 3.2. Subsequently, the transportation of the various waste equipment to the optimal location

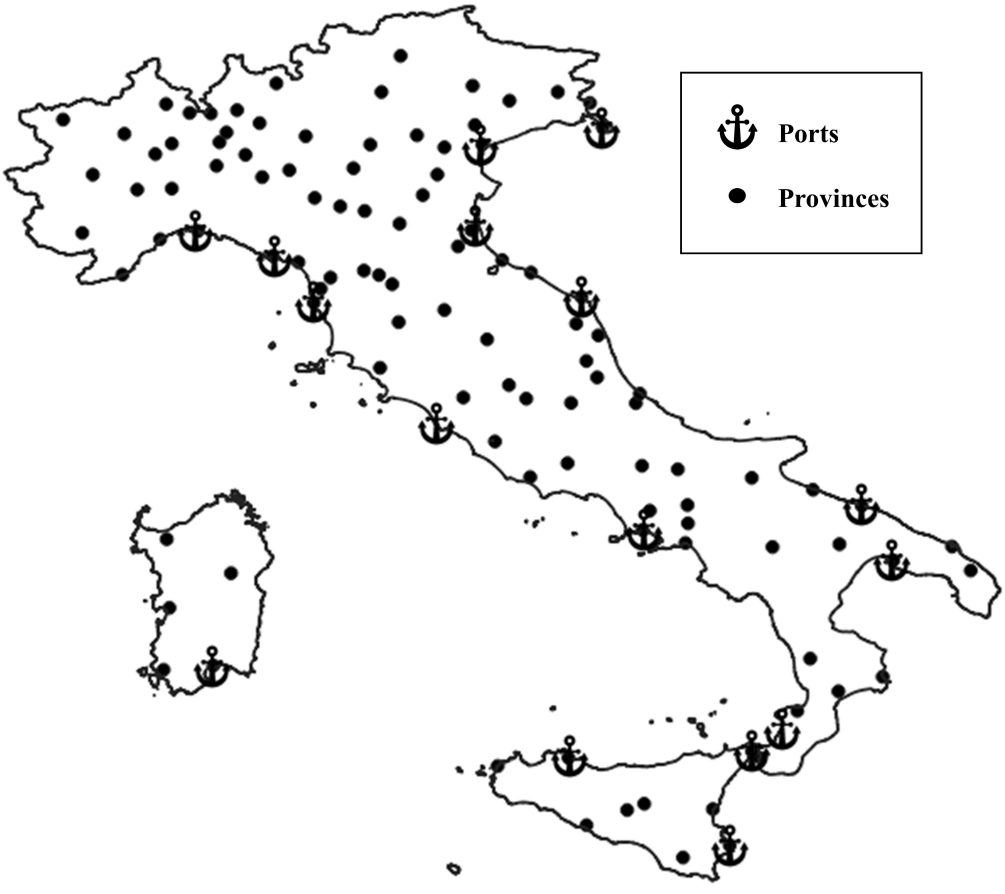

Figure 3.2. *Italian provinces and ports locations*

of the recycling plants is performed by means of heavy-duty trucks for road transport and barges for sea transport, in order to connect also the two main islands present in the Italian territory, namely Sicily and Sardinia, to the mainland. For the sake of simplicity, this thesis work disregards the presence of smaller islands. The truck and barge costs are retrieved from ANL (2019), and are reported in Table 3.2. Lithium batteries and

Table 3.2. *Specific costs of the different transport modes [€/t/km)]*

Transport mode	Class 9 Hazardous	Non-hazardous
Heavy heavy-duty truck	9.38	0.21
Barge	0.29	0.01

magnetized materials are included in the Class 9 section, as miscellaneous goods, of the list of hazardous materials for transport of the U.S. Department of Transportation

(DOT) (HAZMAT, 2024). Thus, an increased cost is considered for their transport. The optimal locations for the recycling plants are selected from among the different provinces. This means that if a recycling plant for a particular technology is to be installed in a province, it is assumed to be located in the same place as the provincial capital. For the recycling facilities to be installed, five possible sizes are introduced, whose minimum and maximum capacities are reported respectively in Tables 3.3 and 3.4.

Table 3.3. *Minimum capacities of the different recycling plants [t/year].*

Technology	small	medium-small	medium	medium-large	large
PV	100	8760	25000	87600	150000
BATT	100	500	1000	5000	13000
MAG	36.5	50	100	200	350

Table 3.4. *Maximum capacities of the different recycling plants [t/year].*

Technology	small	medium-small	medium	medium-large	large
PV	8760	25000	87600	150000	260000
BATT	500	1000	5000	13000	20000
MAG	50	100	200	350	500

The size ranges are selected based on the total quantities of waste equipment available in the different considered scenarios. The total cost for each recycling plant, along with the scaling methods for capital expenditures (CAPEX) and operational expenditure (OPEX), were addressed utilising the different sources cited in Chapter 2. In particular, Cui et al. (2022) is used to retrieve the costs for PV recycling, while ANL (2019) is used for lithium batteries and Chowdhury et al. (2021) for NdFeB magnets. Since Chowdhury et al. (2021) does not directly report a scaling criteria, for NdFeB magnets recycling the same scaling criteria of PV panels is considered in this thesis work. The costs for the different facilities are reported in Table 3.5.

Table 3.5. *Total costs of the different recycling plants [€/t/year)]*

Technology	small	medium-small	medium	medium-large	large
PV	590	570	390	319	227
BATT	68610	34720	8230	4050	3080
MAG	10473	10034	9764	9623	9559

The main data inputs of the model are the following:

- the coordinates of all the provincial capitals and the main Italian ports;

- the availability of waste materials in each province for the different scenarios;
- plant maximum and minimum capacities;
- total recycling costs for each technology for the different size ranges;
- truck and ship specific transportation costs;
- distances between the different ports, retrieved from SEADISTANCES.ORG (2024);
- a value for the tortuosity factor of the Italian roads, equal to 1.4 (Zamboni et al., 2009). This value is needed as a correction factor for the calculation of the distance between two points, which otherwise would be performed considering the Italian roads as perfectly straight, hence resulting in potentially large errors.

3.2 Mathematical formulation

The model formulation contains the following sets:

- $n = \{n_1 - n_{123}\}$: all 123 nodes in the model;
- $p(n) = \{p_1 - p_{107}\}$: Subset of n comprising the Italian provinces;
- $ports(n) = \{port_1 - port_{16}\}$: Subset of n comprising the main Italian ports;
- $p_{\text{sard}}(n)$: Subset of n comprising Sardinia provinces;
- $p_{\text{no sard}}(n)$: Subset of n comprising all the Italian provinces without Sardinia ones;
- $p_{\text{sic}}(n)$: Subset of n comprising Sicily provinces;
- $p_{\text{no sic}}(n)$: Subset of n comprising all the Italian provinces without Sicily ones;
- $t = \{PV, BATT, MAG\}$: set of the three considered green technologies;
- $k = \{small, medium - small, medium, medium - large, large\}$: set of the five different possible size ranges;
- np: Alias set of n, useful to distinguish between departure and arrival nodes;
- r: Alias set of $p(n)$, used for the possible recycling plants locations;

- $ports_n(n)$: Alias set of $ports(n)$ used for arrival ports.

The main input parameters are:

- $Lat(n)$: latitude of all nodes [rad];
- $Long(n)$: longitude of all nodes [rad];
- $Q(n,t)$: availability of waste materials at location n, for technology t [t/year];
- $D_{ports}(n,np)$ Ports distances [km];
- $CAP_{min}(t,k)$: minimum plant capacity for technology t, and size k [t/year];
- $CAP_{max}(t,k)$: maximum plant capacity for technology t, and size k [t/year];
- $PC(t,k)$: plant costs, for technology t and size k [€/t/year];
- $TR(t)$: specific truck costs [€/t/km];
- $SH(t)$: specific barge costs [€/ton/km].

While the main scalars introduced in the model are:

- $\tau = 1.4$: Tortuosity factor of the Italian roads;
- $R = 6372.785$: Earth radius [km];

The continuous variables introduced in the model are:

- $x(n,np,t)$: quantity to be transported from node n to node np, for technology t [t/year];
- $x_{tr}(n,np,t)$: quantity to be transported via truck from node n to node np [t/year];
- $x_{sh}(n,np,t)$: quantity to be transported via barge from $ports$ to $ports_n$ [t/year];
- $x_{av}(n,t,k)$: total quantity arriving to a recycle plant r of technology t and size k [t/year];
- TPC_{PV}: total plant costs of all PV panels recycling plants [€/year]
- TPC_{BATT}: total plant costs of all EV lithium batteries recycling plants [€/year];
- TPC_{MAG}: total plant costs of all NdFeB magnets recycling plants [€/year];

- TPC: total plant costs [€/year];
- TR_{TRAN}^{PV}: PV panels truck transport costs [€/year];
- TR_{TRAN}^{BATT}: EV lithium batteries truck transport costs [€/year];
- TR_{TRAN}^{MAG}: NdFeB magnets truck transport costs [€/year];
- TR_{TRAN}: total truck transport costs [€/year];
- SH_{TRAN}^{PV}: PV panels ship transport costs [€/year];
- SH_{TRAN}^{BATT}: EV lithium batteries ship transport costs [€/year];
- SH_{TRAN}^{MAG}: NdFeB magnets ship transport costs [€/year];
- SH_{TRAN}: total ship transport costs [€/year];
- $TRAN_{TOT}$: total transport costs [€/year];

Three binary variables are introduced in the model:

- $y_{rp}(r,t,k)$: 1 if recycle plant r of technology t and capacity k is installed, 0 otherwise;
- $\lambda_{truck}(n,np,t)$: 1 if truck transport is selected from node n to np for technology t, 0 otherwise;
- $\lambda_{ship}(n,np,t)$: 1 if ship transport is selected from node n to np for technology t, 0 otherwise.

The objective function of the model is:

$$fobj = TRAN_{TOT} + TPC \quad . \tag{3.1}$$

The equations of the model are now described. The mass balance equation for each node n, and for each technology t reads:

$$Q(n,t) + \sum_{np} x(np,n,t) = \sum_{k} x_{av}(n,t,k) + \sum_{np} x(n,np,t) \quad \forall n,t. \tag{3.2}$$

Where $Q(n,t)$ represents the availability of waste materials in each province for the different technologies [t/year]. $x(np,n,t)$ represents the quantity to be transported from node n to node np [t/year]. $x_{av}(n,t,k)$ is the total quantity arriving to a recycle plant r

of technology t and size k [t/year]. It is straightforward to note that the total quantity to be transported ($x(np,n,t)$) has to be the sum of the quantity to be transported by means of trucks and the one transported by means of ships:

$$x(n,np,t) = x_{tr}(n,np,t) + x_{sh}(n,np,t) \quad \forall n,t. \tag{3.3}$$

$x_{tr}(n,np,t)$ denotes truck transportation quantity from node n to np for technology t [t/year] , while $x_{sh}(n,np,t)$ represents ship transportation quantity from node n to np for technology t [t/year] . Two binary variables are used: $\lambda_{truck}(n,np,t)$ equals 1 if truck transport is chosen from node n to np for technology t, otherwise 0. Similarly, $\lambda_{ship}(n,np,t)$ equals 1 if ship transport is chosen from node n to np for technology t, otherwise 0. To effectively integrate these binary variables, two equations enforce "big M" constraints, setting limits on truck and ship transportation quantities using a large constant M. The described equations are:

$$x_{sh}(n,np,t) \leq M \cdot \lambda_{\text{ship}}(n,np,t) \quad \forall n,np,t \quad , \tag{3.4}$$

$$x_{tr}(n,np,t) \leq M \cdot \lambda_{\text{truck}}(n,np,t) \quad \forall n,np,t \quad . \tag{3.5}$$

After that, the total quantity $x_{av}(n,t,k)$ of Eq. (3.2) arriving to a recycle plant r of technology t and size k [t/year] is constrained by the maximum and minimum capacity of a recycling plant:

$$x_{av}(r,t,k) \geq CAP_{min}(t,k) \cdot y_{rp}(r,t,k) \quad , \tag{3.6}$$

$$x_{av}(r,t,k) \leq CAP_{max}(t,k) \cdot y_{rp}(r,t,k) \quad . \tag{3.7}$$

$CAP_{min}(t,k)$ and $CAP_{max}(t,k)$ represent the minimum and maximum capacities of the plants of different technologies and of different sizes, which are reported in Tables 3.3 and 3.4. $y_{rp}(r,t,k)$ is a binary variable that takes the value of 1 if a recycle plant is installed in location r, for technology t and of capacity k, 0 otherwise Then, an additional constraint is added to limit the selection of only one size of a recycling plant for every location r of each technology t:

$$\sum_k y_{rp}(r,t,k) \leq 1 \quad . \tag{3.8}$$

Subsequently, the cost equations are introduced into the model. The total cost of the entire supply chain, namely the objective function, as reported in Eq. 3.1.

The total processing costs are the sum of the PV panles, EV lithium batteries and NdFeB magnets processing costs:

$$TPC = TPC_{PV} + TPC_{BATT} + TPC_{MAG} \quad , \tag{3.9}$$

$$TPC = \sum_{(n,k)} x_{av}(n,t,k) \cdot PC(t,k) \quad \forall t. \tag{3.10}$$

Where $PC(t,k)$ represent the costs of the different recycling technologies, for different size ranges, as previously introduced in Table 3.5. Then, total transport cost is given by the quantity transported via truck and via ship:

$$TRAN_{TOT} = TR_{TRAN} + SH_{TRAN} \tag{3.11}$$

$$TR_{TRAN} = \sum_{(n,np,t)} TR(t) \cdot D(n,np) \cdot x_{tr}(n,np,t) \cdot \tau \quad , \tag{3.12}$$

Where τ is the tortuosity factor, $TR('technology')$ represent the different specific truck transport costs of each technology, as previously introduced in Table 3.2. $D(n,np)$ is the distance between node n and node np, calculated with the formula for the minimum distance between two points of a sphere:

$$\begin{aligned} D(n,np) = R_{earth} \cdot \{&\arccos[\sin(Lat(n)) \cdot \sin(Lat(np))] \\ &+ \cos(Lat(n)) \cdot \cos(Lat(np)) \cdot \cos[Long(n) - Long(np)]\} \quad . \end{aligned} \tag{3.13}$$

Where R_{earth} represents the Earth radius, while $Lat(n)$, $Lat(np)$, $Long(n)$ and $Long(np)$ are respectively the latitude and the longitude of nodes n and np. The ship transport costs are instead computed as:

$$SH_{TRAN} = \sum_{(n,np,t)} (SH(t) \cdot D_{ports}(n,np)) \cdot x_{sh}(n,np,t)] \quad . \tag{3.14}$$

Where D_{PORTS} is the matrix of distances between the different Italian ports, and it's imported as a table in the model. $SH('technology')$ represent instead the different specific ship costs of each technology, as previously outlined in Table 3.2.

To model the transport routes and select the locations for recycling plant installation, variable fixing has been performed as follows. Port locations cannot represent the end points of the supply chain:

$$x_{av}(n,t,k) = 0 \quad \forall n = ports, t, k \tag{3.15}$$

In order to model the transport routes the following variable fixing has been performed: truck transport is not allowed from one port location to another port.

$$\lambda_{truck}(n,np,t) = 0 \quad \forall n = ports, np = ports_n, t \tag{3.16}$$

$$x_{tr}(n,np,t) = 0 \quad \forall n = ports, np = ports_n, t \tag{3.17}$$

Ship transport is not allowed to connect two provinces, or a province and a port, or a port and a province:

$$\lambda_{ship}(n,np,t) = 0 \quad \forall n = p, np = r, t \tag{3.18}$$

$$x_{sh}(n,np,t) = 0 \quad \forall n = p, np = r, t \tag{3.19}$$

$$\lambda_{ship}(n,np,t) = 0 \quad \forall n = p, np = ports, t \tag{3.20}$$

$$x_{ship}(n,np,t) = 0 \quad \forall n = p, np = ports, t \tag{3.21}$$

$$\lambda_{ship}(n,np,t) = 0 \quad \forall n = ports, np = p, t \tag{3.22}$$

$$x_{ship}(n,np,t) = 0 \quad \forall n = ports, np = p, t \tag{3.23}$$

Obviously, truck transport directly from a province location on an island to another province location on the mainland (and vice versa) is not feasible, thus:

$$\lambda_{truck}(n,np,t) = 0 \quad \forall n = p_{sard}, np = p_{nosard}, t \tag{3.24}$$

$$x_{truck}(n,np,t) = 0 \quad \forall n = p_{sard}, np = p_{nosard}, t \tag{3.25}$$

$$\lambda_{truck}(n,np,t) = 0 \quad \forall n = p_{nosard}, np = p_{sard}, t \tag{3.26}$$

$$x_{truck}(n,np,t) = 0 \quad \forall n = p_{nosard}, np = p_{sard}, t \tag{3.27}$$

$$\lambda_{truck}(n,np,t) = 0 \quad \forall n = p_{sic}, np = p_{nosic}, t \tag{3.28}$$

$$x_{truck}(n,np,t) = 0 \quad \forall n = p_{sic}, np = p_{nosic}, t \tag{3.29}$$

$$\lambda_{truck}(n,np,t) = 0 \quad \forall n = p_{nosic}, np = p_{sic}, t \tag{3.30}$$

$$x_{truck}(n,np,t) = 0 \quad \forall n = p_{nosic}, np = p_{sic}, t \tag{3.31}$$

The presented model has been formulated as a MILP problem with the objective of minimising the total cost of the critical raw material supply chain at the Italian level. GAMS software is utilized to solve the model using the CPLEX solver.

Chapter 4

Results and discussion

Chapter 4 focuses on the results of the supply chain model, analysing the locations of the installed recycling plants, and the material flows across different scenarios. Additionally, economic considerations are explored, along with an analysis of computational performance.

4.1 Economic evaluations

4.1.1 Costs of the supply chain for the different scenarios

The different costs for the analysed scenarios are reported in Table 4.1. It can be noted that for all scenarios the total processing costs are greater than the total transport costs. In particular, in the base case, the total costs are 65 M€/year, 92% of which is represented by the processing costs. For the STEPS scenario, again the difference between the two is almost one order of magnitude, and processing costs in this case are 80% of the objective function value. For the APS and NZE scenarios, processing costs are instead respectively 82 and 81% of the total costs of the supply chain. It can also be observed that the truck transport costs are generally higher than the ship transport ones. In particular, for the base case the truck transport costs are 4.34 M€/year, and represent 88% of the total transport costs. For STEPS, APS and NZE scenarios, the truck costs turn out to be respectively 24, 26 and 25 M€/year, representing thus 85, 85 and 84% of the total transport costs. The APS scenario results to be characterised by the largest total costs, namely the highest value of the objective function, which results to be 163 M€/year. This is due to the fact that the APS scenario, despite having a total waste material quantity that is lower than the one of the NZE scenario, considers a greater growth rate for EV lithium batteries. This results in a greater total quantity of waste EV lithium batteries, that increases the processing costs, and also the truck costs, since lithium batteries are hazardous materials, hence their transport results more expensive.

Table 4.1. *Costs of the supply chain for the four different scenarios [M €/year].*

	Base case	**STEPS**	**APS**	**NZE**
Total proc. costs PV	27.11	63.60	81.40	81.60
Total proc. costs BATT	32.06	47.40	48.00	46.10
Total proc. costs MAG	1.06	2.66	3.32	3.58
Total proc. costs	**60.23**	**114.00**	**133.00**	**131.00**
Truck costs PV	1.60	4.59	5.91	5.91
Truck costs BATT	2.62	19.30	19.50	18.80
Truck costs MAG	0.12	0.28	0.25	0.24
Total truck costs	**4.34**	**24.20**	**25.70**	**24.90**
Ship costs PV	0.23	0.65	0.84	0.87
Ship costs BATT	0.35	3.78	3.83	3.67
Ship costs MAG	0.02	0.04	0.03	0.03
Total ship costs	**0.60**	**4.47**	**4.69**	**4.57**
Total transport costs (truck + ship)	**4.94**	**28.60**	**30.40**	**29.50**
Total costs (objective fun)	**65.17**	**142.00**	**163.00**	**161.00**

4.1.2 Evaluation of recycling economic sustainability

In order to assess the potential, in economical terms, of the analysed recycling processes and their supply chains, a total cost estimate should be performed for each material. Therefore the total costs, meaning both processing and transport costs are computed for each green technology, and then a cost allocation is done to allocate the different costs among the various CRM, in a way that it results proportionate to the value of the material, namely its market price, and to its actual content within the recycled equipment. The selected allocation technique is the one used by Chowdhury et al. (2021), in particular in the supplementary material. In this article, an output value of 1 kg of one material is taken as a reference, and the quantities of the other output materials are calculated respectively, based on the actual composition. Then, the market prices of the different virgin materials are retrieved and store. Then, in order to find the economic ratio, to be used for cost allocation, for each material, the product of the output quantity is multiplied by the price, and divided by the sum of all the products between output quantity and associated price of the virgin material:

$$ER = \frac{O_i \cdot P_i}{\sum_i O_i \cdot P_i} \quad . \tag{4.1}$$

Where ER is the economic ratio, O_i represents the output quantity, and P_i the market price of the CRM. Following this approach, the different economic ratios, expressed as percentages, are obtained. The latter are reported in Table 4.2. Then, using these

Table 4.2. *Economic ratios for cost allocation for the different materials.*

Technology	Element	%
PV	**Al**	19.1
	Cu	8.65
	Si	7.93
BATT	**Al**	6.13
	Co	42.8
	Cu	14.8
	Li	26.2
	Mn	1.6
	Ni	1.2
MAG	**Nd**	77
	Pr	9
	Dy	7

ratios, the actual allocation is performed, and the resulting costs together with the market prices of the materials are reported in Tables 4.3, 4.4, 4.5. The transport costs are affected by the selected scenario, but since their contribution in the total costs is limited, the differences between the various scenarios in this case are negligible.

Table 4.3. *Recycling costs allocated to the different elements and market prices, for PV panels [€/kg]*

Technology	Element	Size	Cost	Virgin Price
PV	**Al**	small	0.12	2.06
		med-small	0.11	
		medium	0.08	
		med-large	0.07	
		large	0.05	
	Cu	small	0.05	7.46
		med-small	0.05	
		medium	0.04	
		med-large	0.03	
		large	0.02	
	Si	small	0.05	1.9
		med-small	0.05	
		medium	0.03	
		med-large	0.03	
		large	0.02	

Table 4.4. *Recycling costs allocated to the different elements and market prices, for EV lithium batteries [€/kg]*

Technology	Element	Size	Cost	Virgin Price
BATT	Al	small	4.24	2.06
		med-small	2.16	
		medium	0.54	
		med-large	0.28	
		large	0.22	
	Co	small	29.58	30.78
		med-small	15.08	
		medium	3.74	
		med-large	1.95	
		large	1.53	
	Cu	small	10.23	7.46
		med-small	5.21	
		medium	1.29	
		med-large	0.67	
		large	0.53	
	Li	small	18.11	18.84
		med-small	9.23	
		medium	2.29	
		med-large	1.19	
		large	0.94	
	Mn	small	1.11	1.66
		med-small	0.56	
		medium	0.14	
		med-large	0.07	
		large	0.06	
	Ni	small	0.88	15.293
		med-small	0.48	
		medium	0.16	
		med-large	0.11	
		large	0.10	

It's worth noting that the costs of recycled materials are significantly lower than those of virgin materials. However, it's important to recognise that this comparison is based on an initial estimate of recycling costs, which requires further refinement for a more accurate understanding of the differences. Comparing material procurement costs directly with market prices isn't the most precise method, as market prices can be influenced by various factors beyond just production costs. Additionally, market prices can be volatile due to geopolitical uncertainties in relevant countries. However, despite these considerations, the analysis highlights the significant potential of CRM recycling. While acknowledging limitations, the results provide evidence supporting the viability of recycling critical raw materials. This evidence suggests a promising path for the expansion of the recycled materials market, offering opportunities for sustainable resource management.

Table 4.5. *Recycling costs allocated to the different elements and market prices, for NdFeB magnets [€/kg]*

Technology	Element	Size	Cost	Virgin Price
MAG	Dy	small	0.82	191.21
		med-small	0.79	
		medium	0.77	
		med-large	0.76	
		large	0.76	
	Nd	small	9.04	34.83
		med-small	8.70	
		medium	8.49	
		med-large	8.38	
		large	8.33	
	Pr	small	1.06	34.81
		med-small	1.02	
		medium	0.99	
		med-large	0.98	
		large	0.97	

4.2 Model results

4.2.1 Base case scenario

For the base case scenario, namely the 2031 one, the total cost of the supply chain is 65.17 M€/year, of which 60.23 M€/year are process costs, while 4.34 M€/year are instead transport costs. The supply chain configurations are depicted in Figure 4.1. It can be observed that in Northern Italy, two recycling facilities for EV lithium batteries are installed, while a third one is installed in Naples to collect and recycle the waste equipment from the Southern part of the country. The choice of installing two plants in the North of Italy, is due to the fact that the EV distribution in the Italian peninsula is not uniform. Indeed the presence of EV is greater in the northern part of the country, especially in the regions of Trentino Alto Adige and Lombardia, where the recycling facilities are installed. For NdFeB magnets only one recycling facility is installed in the whole country, in particular in Messina. This outcome is attributed to the concentration of wind turbines in the South, thus making it more economically viable to establish a single recycling facility there in order to minimise the transportation of waste equipment across the country. For PV panels two plants of similar capacity are installed both in the central part of the country, in particular in Livorno and Ancona. These two locations are strategical ones, since they both have a port, and are situated in the two coasts of the peninsula. In this way, the city of Livorno receives directly via barge the waste panels of the islands and of the western coast, while the eastern coast is covered by the plant in Ancona. Photovoltaic panels, are spread almost uniformly across the Italian peninsula, and this is the reason why the two facilities are installed near the centre of the country. Due to the complexity involved in illustrating the diverse

Figure 4.1. *Graphical results for the base case scenario.*

material flows within the supply chain across Italy, a simplified depiction is used. As a result, Figure 4.2 exclusively showcases the sea transport trajectories for the different green technologies. Additionally, in the case of truck transport, the trajectories are omitted from the map representation because including them would result in an overwhelming number of lines. However, if they were included, they would be depicted as straight lines from each province to either the closest selected recycling plant or to the closest port. Similarly, they would also be represented as straight lines from the closest arriving port to the selected recycling plant. This focused presentation aims to enhance clarity and facilitate a deeper understanding of the results. In each case, it is evident that one or two main ports emerge as the primary destinations for the majority of waste equipment transportation. For EV lithium batteries and NdFeB magnets the main arrival port is in Naples, while for PV panels the main destinations are Ancona and Livorno, which are the two locations where the recycling facilities are installed in this case. Ship transport is not used only to connect the islands with the mainland: indeed in some cases, especially for long distances, this type of transport is preferred with respect to truck transport. This is due to the fact that barge costs are lower than the truck ones. In particular, it can be noted that for each port a certain quantity of each waste technology is delivered via ship. This means that even if the final destination could be reached with trucks following a shorter route, the barge transport is always selected if the province from where the materials are delivered contains a port. Moreover, in the case of magnetized materials and lithium batteries, this difference in cost between the two means of transport is even more significant, since for hazardous materials the truck costs increase in a much pronounced way.

The sizes of the selected plants are detailed in Table 4.6.

Table 4.6. *Sizes and locations of the different recycling plants for the base case scenario [t/year].*

	Province	Small	Medium-small	Medium	Medium-large	Large
BATT	Milano	/	/	1000	/	/
	Trento	/	/	1000	/	/
	Napoli	/	/	1895	/	/
PV	Livorno	/	/	36442	/	/
	Ancona	/	/	33079	/	/
MAG	Napoli	/	/	109	/	/

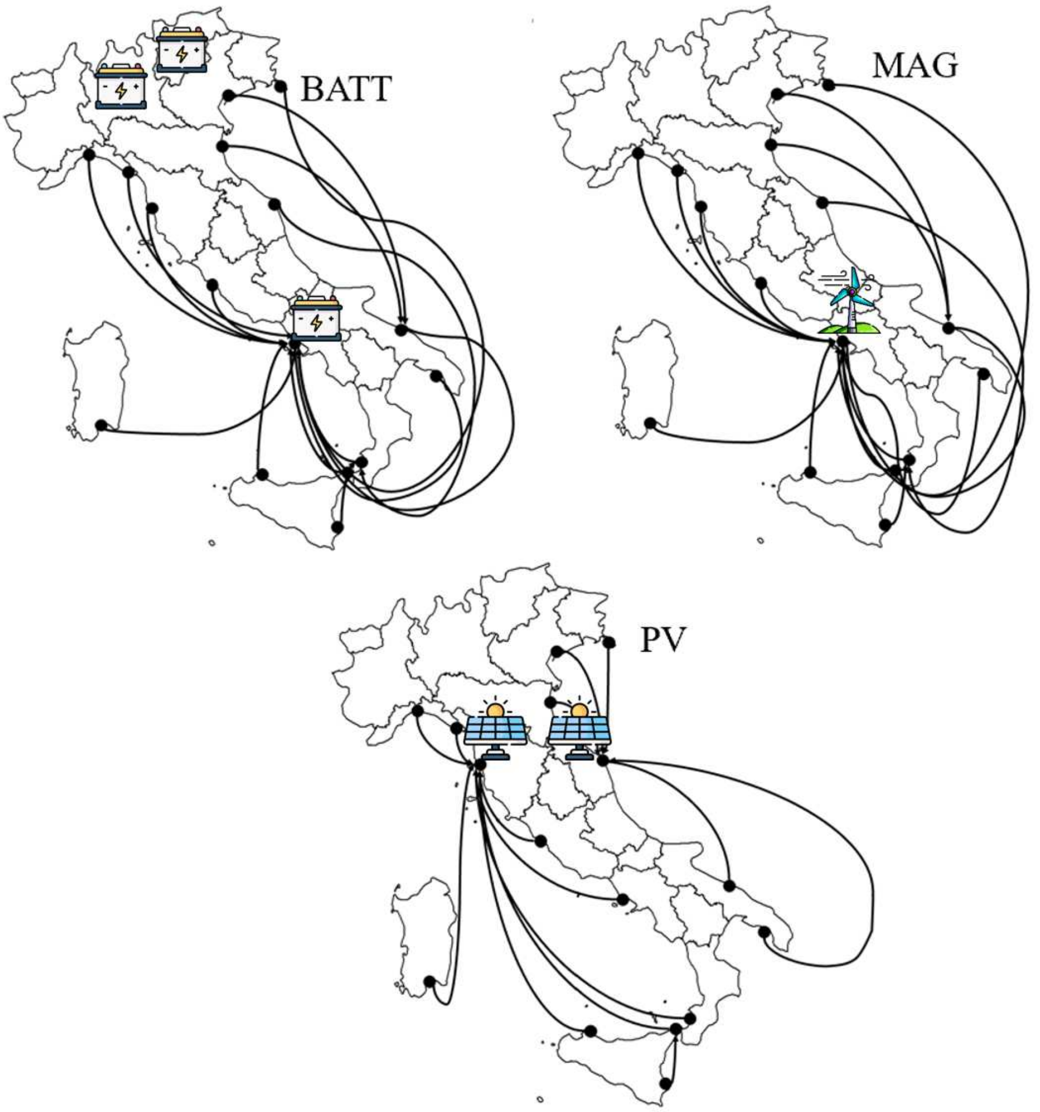

Figure 4.2. *Sea transport trajectories for the three analysed green technologies for the base case.*

4.2.2 STEPS scenario

In the STEPS scenario the total cost of the supply chain is 142 M€/year, divided in 114 M€/year as processing costs and 24.2 M€/year as transport costs. The STEPS scenario considers the tangible measures that governments are actually undertaking, to realise their energy objectives. For this scenario in the year 2050, the graphical results are depicted in Figure 4.3. In this scenario, compared to the base case scenario previously presented, it is economically advantageous to install a single large recycling plant for EV lithium batteries in the city of Livorno, rather than multiple smaller ones.

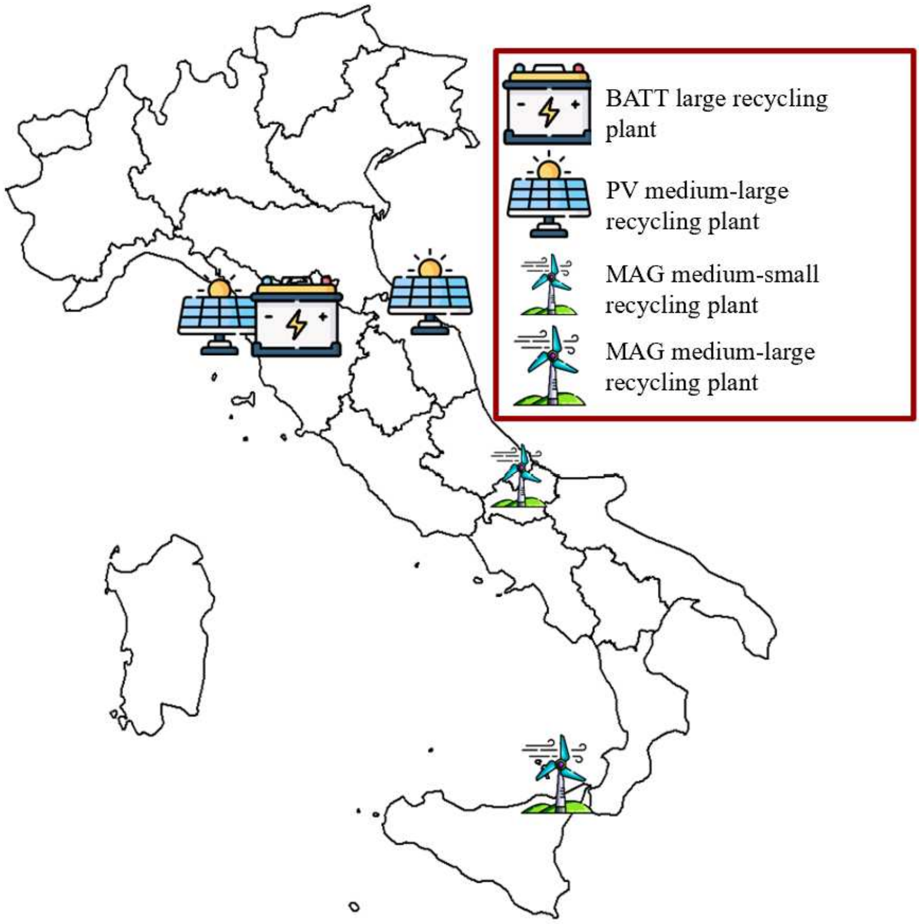

Figure 4.3. *Graphical results for the STEPS scenario.*

This is due to the effect of economies of scale on the processing costs. Despite the increase in transport costs when materials from across the country must converge at a single location, these costs are offset by the savings achieved through the efficiency of larger-scale recycling facilities. This is exemplified by the installation of two medium-large recycling facilities for PV panels in central Italy, situated in Livorno and Ancona. Hence, the advantageous impact of economies of scale is evident in this case as well. In the STEPS scenario, for NdFeB magnets, two recycling plants are installed in the southern part of the country, comprising a medium-small facility in Campobasso and a medium-large one in Messina. The sea transport trajectories are illustrated in Figure 4.4. Notably, there are few main ports where materials are directed, with Livorno serving as the main port for lithium batteries, Messina for magnets, and Livorno and Ancona for PV panels. The main difference between this scenario and the previous base case scenario lies in the fact that the total quantity of waste materials increases by

192%. This is the reason why the large recycling plant is chosen for the EV lithium batteries. As the quantity of waste batteries increases sufficiently, it becomes feasible to install a large recycling plant. This, in turn, allows for a reduction in processing costs due to economies of scale effects. The increase in the waste materials quantity leads also to the increase in size of the two PV panels recycling plants, which become medium-large ones, remaining in the same cities as the base case scenario.

The sizes and locations of the installed recycling plants are detailed in Table 4.7.

Table 4.7. *Sizes and locations of the different recycling plants for the STEPS scenario [t/year]*

	Province	Small	Medium-small	Medium	Medium-large	Large
BATT	**Livorno**	/	/	/	/	15392
PV	**Livorno**	/	/	/	104478	/
	Ancona	/	/	/	94836	/
MAG	**Messina**	/	/	/	224	/
	Campobasso	/	50	/	/	/

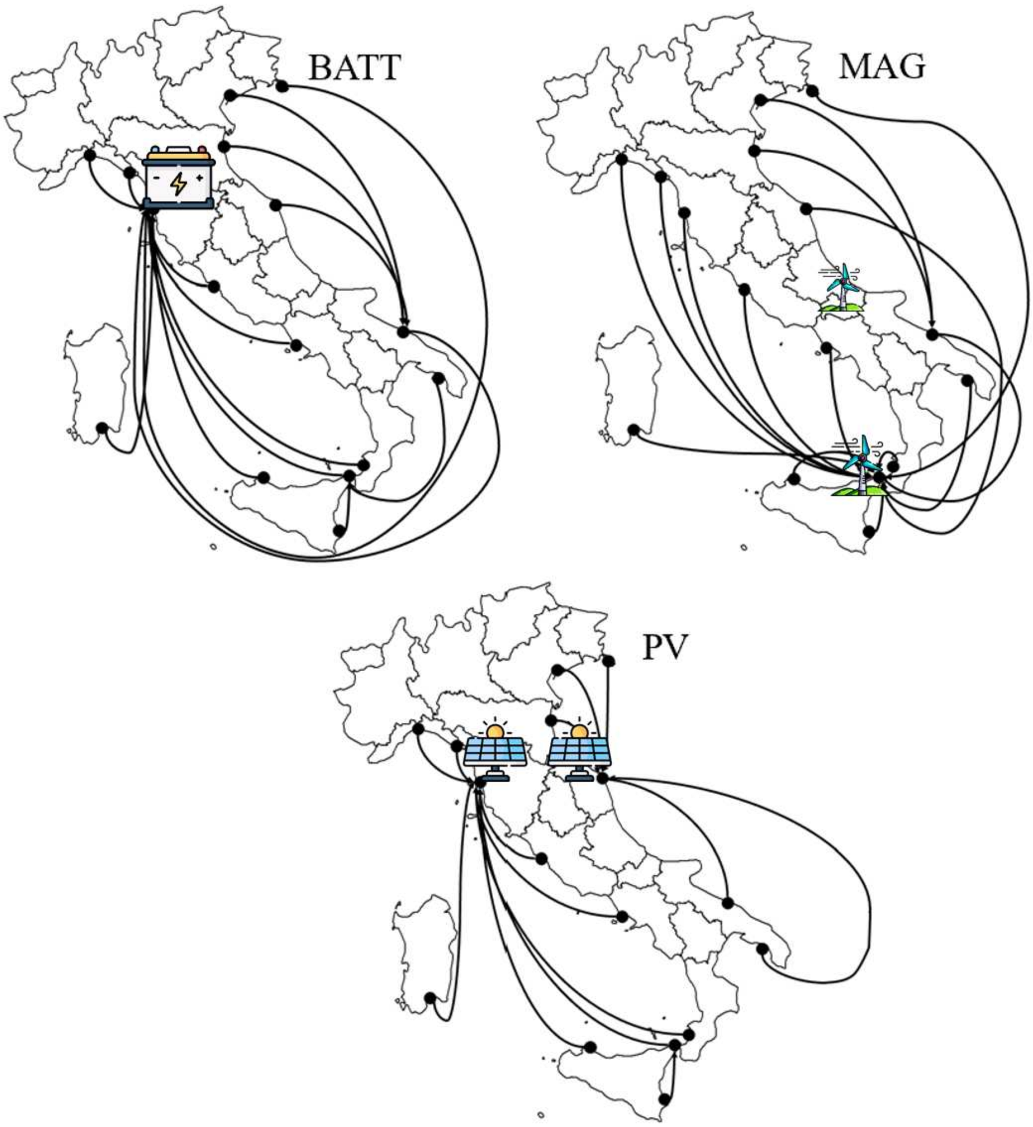

Figure 4.4. *Sea transport trajectories for the three analysed green technologies in the STEPS scenario.*

4.2.3 APS scenario

The total costs of this scenario are 163 M€/year, of which 133 M€/year are processing costs, and the other 30 M€/year are transport ones. The APS scenario, respect to the STEPS one, assumes that the different governments will fulfill their climate commitments. Therefore, it straightforward that in this case, respect to the previous ones, the waste material quantities increase. Indeed, the total quantity of waste materials in this scenario, increases by 26%, with respect to the STEPS one, resulting also in a cost increase of 15%. For this scenario for the year 2050, the graphical results are represented in Figure 4.5. In this case it can be seen that other two small recy-

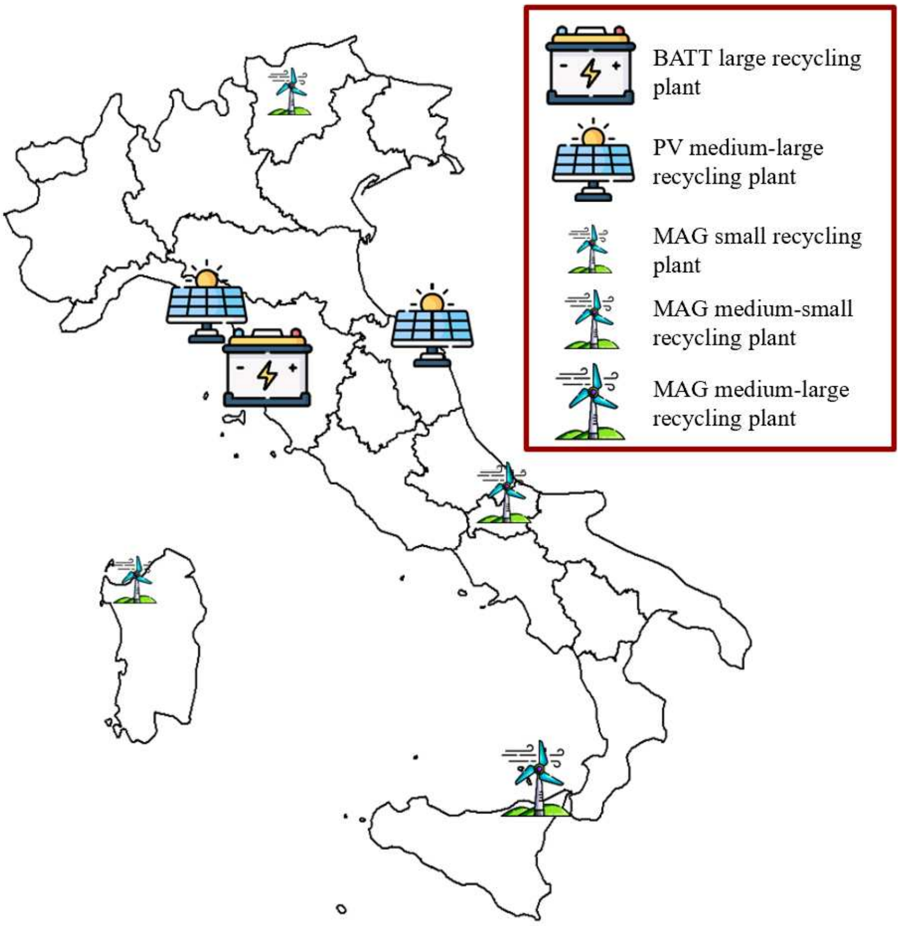

Figure 4.5. *Graphical results for the APS scenario.*

cling plants for NdFeB magnets are installed in the cities of Sassari and Trento. These small-scale recycling plants are installed because, in the case of NdFeB magnets, it is more advantageous to distribute the waste material among several smaller recycling facilities rather than installing a single large facility. This phenomenon arises because the quantities involved for rare earth magnets are relatively small compared to other technologies. Consequently, the benefits of economies of scale are limited. As a result, the increased transportation costs incurred in moving materials towards a single recycling plant outweighs the savings generated by economies of scale. On the other hand, in the case of EV lithium batteries, where the quantities are higher, the result is the opposite. Indeed, one single recycling plant is opened for the entire country, whose position remains the same as in the previous scenarios, even though its size increases. The selected location is Livorno, which is a strategic one, since the recycling plant installed, results to be close to the port. Thus, ship transport can be exploited without the need for further large movement of the materials via truck. Also in the case of PV panels two strategic locations are chosen for the same reason. However, for this scenario, with respect to the previous ones, the position of the western plant is slightly changed, since it needs to be installed in La Spezia. As a general observation, it's worth noting that barge transport is often favored for long distances due to its lower specific costs compared to truck transport. Therefore, utilising this mode of transport enables the movement of various materials across the country without significantly escalating expenses. The sizes of the different recycling facilities, together with their location, are reported in Table 4.8.

Table 4.8. *Sizes and locations of the recycling plants for the APS scenario [t/year].*

	Province	**Small**	**Medium-small**	**Medium**	**Medium-large**	**Large**
BATT	Livorno	/	/	/	/	15583
PV	La Spezia	/	/	/	127027	/
	Ancona	/	/	/	127992	/
MAG	Trento	37	/	/	/	/
	Campobasso	/	50	/	/	/
	Sassari	37	/	/	/	/
	Messina	/	/	/	213	/

The sea transport trajectories for the APS scenario are depicted in Figure 4.6, where it can be seen that in the case of lithium batteries the flow lines are again mainly directed towards the port of Livorno. Regarding NdFeB magnets the material transport is all directed towards Messina, while for PV panels there are two main destinations, which are La Spezia and Ancona.

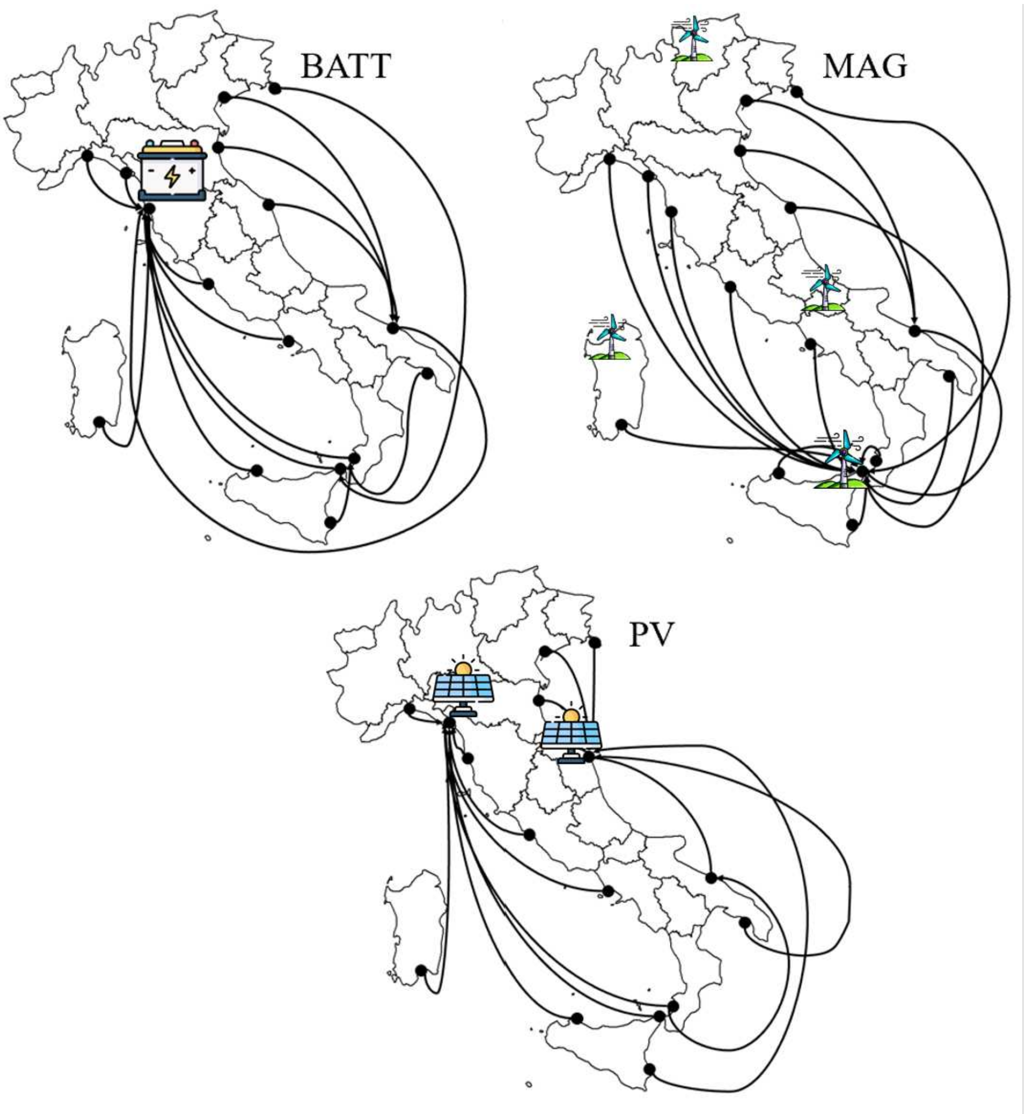

Figure 4.6. *Sea transport trajectories for the APS scenario.*

4.2.4 NZE scenario

The total costs of the NZE scenario are 161 M€/year, of which 131 M€/year are processing costs and 25 M€/year are related to the transport of the waste materials. This scenario, considers the changes needed to be performed in order to mitigate the global temperature rise to 1.5 °C above pre-industrial levels by the year 2100. Also in this case, the total quantities increase, even though only by 0.1% with respect to the APS one. It is noteworthy that despite this slight increase in the total quantity of waste materials, the total costs of NZE scenario decrease by 1.2% respect to the APS scenario. This increase is sensible in the case of NdFeB magnets, whose quantity increases by 7%. The total quantity of waste Pv panels remains stable, while the amount of waste EV lithium batteries decreases by 4% respect to the APS scenario. The results, for this case, are graphically reported in Figure 4.7. In this case, for the NdFeB magnets, the

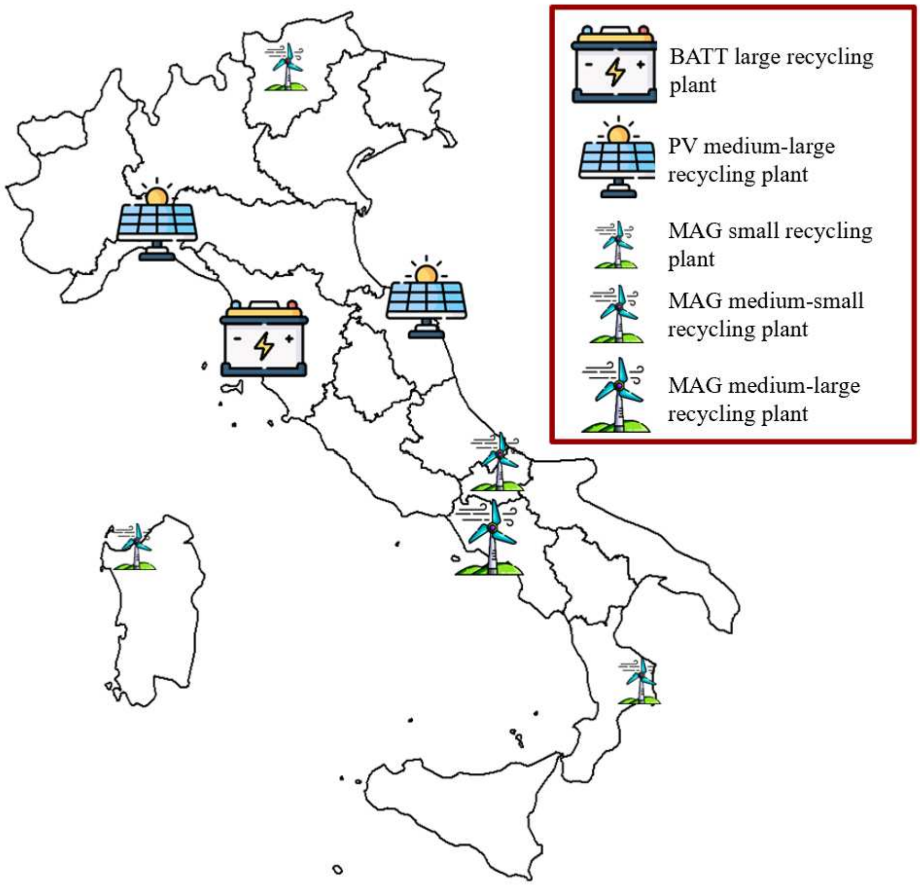

Figure 4.7. *Graphical results for the NZE scanario.*

medium-large recycling facility is moved to Naples, while a new plant is installed in Crotone. Once more, also for this scenario it can be concluded that for rare earth magnets, the quantities are not enough to allow a cost reduction, imputable to the effect of economies of scale, large enough to compensate the increase in transport costs. Thus, as a result, multiple facilities of smaller sizes are installed, being economically more convenient. Concerning the PV panels, again two medium-large plants are opened for the whole country, even though the western one is moved from La Spezia to Genoa. The EV lithium battery recycling facility remains in the city of Livorno, as can be noted in Table 4.9. Even if the total quantity of waste EV lithium batteries slightly decreases, it is still enough to have a sensible scale effect on processing costs, that is able to cover the increase in transport costs, with respect to an hypothetical situation in which multiple facilities are installed. The material flow trajectories of sea transport

Table 4.9. *Sizes and locations of the recycling plants for the NZE scenario [t/year].*

	Province	Small	Medium-small	Medium	Medium-large	Large
BATT	Livorno	/	/	/	/	14962
PV	Genova	/	/	/	129898	/
	Ancona	/	/	/	126027	/
MAG	Trento	37	/	/	/	/
	Campobasso	/	50	/	/	/
	Sassari	37	/	/	/	/
	Crotone	37	/	/	/	/
	Napoli	/	/	/	200	/

for the NZE scenario are represented in Figure 4.8. It can be seen that for EV lithium batteries also in this scenario the waste materials are all directed to the port of Livorno, where the large recycling facility is installed. For PV panels the trajectories are mainly directed towards the ports of Ancona and Genoa, while for rare earth magnets the waste materials convey in the port of Naples.

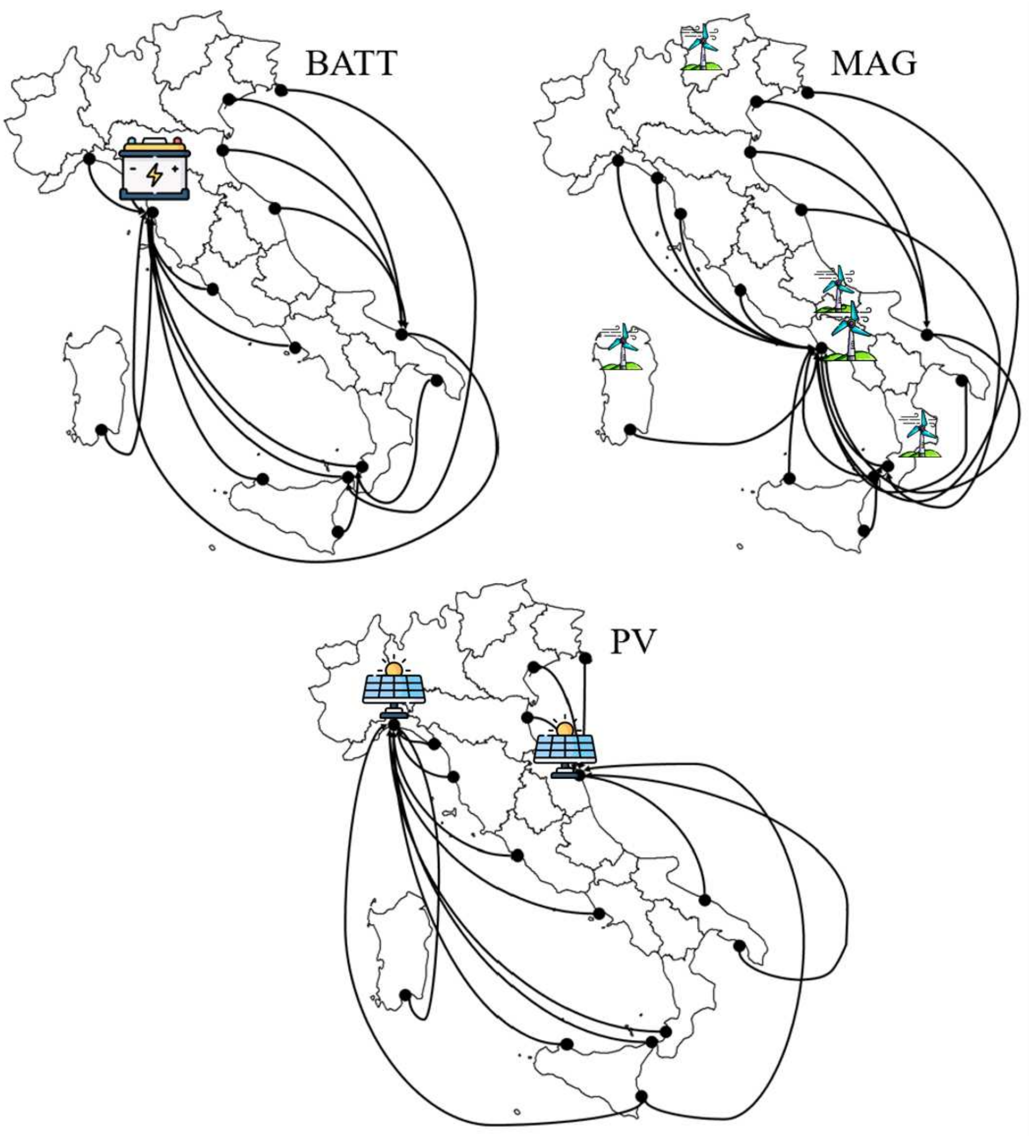

Figure 4.8. *Sea transport trajectories for the NZE scenario.*

4.3 CRM Demand and availability from recycle

The Italian demand of CRM, based on the data extracted from the foresight report on raw materials and strategic supply chains, provided by the EC (JRC, 2023) is reported in Table 4.10.

Data concerning the actual quantity of CRM available from recycling, for the different scenarios, are reported in Table 4.11. It can be concluded that generally, the recycled materials are not enough to sustain the Italian demand, especially in the case of EV lithium batteries and PV panels. However, for NdFeB magnets from EV and wind turbines, the material demand in most of the cases results to be lower than the

Table 4.10. *CRM Italian demand for the three analysed technologies for 2030 and 2050 [t/year]*

		HDS		LDS	
Technology	**Material**	**2030**	**2050**	**2030**	**2050**
PV	**Al**	59028	66396	28688	29329
	Cu	4232	4647	2057	2053
	Si	13673	10673	6645	4714
BATT	**Al**	83359	124719	61819	96576
	Co	6484	3771	4892	3636
	Cu	30389	48476	21642	35894
	Li	7153	10779	5238	7696
	Mn	4741	2609	3422	2571
	Ni	34207	48633	27612	36299
MAG	**Dy**	92	121	26	22
	Nd	687	908	315	340
	Pr	51	67	16	8

Table 4.11. *CRM obtained from hypothetical Italian recycling plants [t/year]*

		BASE	**STEPS**	**APS**	**NZE**
PV	**Al**	5562	15945	20402	20474
	Cu	542	1555	1989	1996
	Si	2127	6099	7804	7831
BATT	**Al**	526	2078	2104	2020
	Co	267	1056	1069	1026
	Cu	351	1385	1402	1347
	Li	245	970	982	943
	Mn	191	754	764	733
	Ni	153	603	611	587
MAG	**Dy**	17	67	68	65
	Nd	957	3780	3827	3675
	Pr	117	463	469	450

actual quantity obtained from the recycling facilities. For example, the Nd and Pr quantities in the APS scenario, obtained from recycling, are respectively 4 and 7 times higher than the actual demand for 2050 in the HDS. The Dy available from the recycling processes, is instead lower than the demand in the HDS scenario. In particular, the Dy available in the STEPS, APS and NZE scenario is respectively 81, 78 and 86% lower than the HDS demand. For the other green technologies, the demand in the HDS scenario is higher than the amount available from recycling. For example the Al demand for PV panels is 4 times higher than the amount available in the STEPS scenario, and more than three times higher than the one available in the APS and NZE scenarios. In the case of lithium batteries, the HDS Li demand is more than 10 times the actual quantity available from recycling in the STEPS, APS and NZE scenarios.

4.4 Overview of the computational performances

The model statistics are reported in Table 4.12, in which "single equations" represent the individual constraints of the model, while "single variables" represent the actual decision variables, namely the unknowns of the problem. On the other hand, "discrete variables" are the variables capable of assuming only specific values, such as binary variables with values restricted to either one or zero. All the parameters and variables whose value is not zero represent the" non-zero elements".

Table 4.12. *Supply chain model statistics*

Blocks of equations	21
Single equations	140075
Blocks of variables	21
Single variables	230399
Non zero elements	465225
Discrete variables	92379

The computational times for the different proposed scenarios are reported in Table 4.13.

Table 4.13. *Computational time for the different scenarios [s].*

	Base case	**STEPS**	**APS**	**NZE**
Computational time	4610	793	3051	4190

All the simulations reached the optimal value for the objective function, so the optimality gap is zero. All the calculations have been performed on a DELL Precision 7560 laptop with Intel(R) Core (TM) i7-11850H @ 2.50GHz 2.50 GHz and 64 GB RAM.

Conclusions

The aim of this Master's Thesis was to propose an economic optimisation of the Italian supply chain for recycling Critical Raw Materials (CRM) found in three green technologies: photovoltaic (PV) panels, electric vehicle (EV) lithium batteries, and NdFeB magnets from EVs and wind turbines. Three distinct recycling processes were examined, each with varying costs and recovery values for different CRMs. The starting points of this supply chain are the provincial capitals, which are assumed to be the collection points of the waste materials of each province. The waste materials are then transported to the respective recycling facility, in order to be processed. Two different transport routes have been selected for this work, namely trucks and barges. The supply chain model formulation was developed using a mixed integer linear programming framework, implemented in GAMS and solved using the CPLEX solver. The aim of the model was to minimise the total cost of the CRM supply chain, which comprehends both transport and processing costs. Different scenarios were analysed: first, a base case forecast for the year 2031 has been performed, in order to obtain the different waste material quantities available for each province in that year. Then, starting from this forecast, three different scenarios have been considered for the year 2050, based on the International Energy Agency (IEA) projections. In particular, the STEPS scenario considers a situation in which the actual policies and laws that the governments are undertaking to realize their energy goals. The APS scenario explores instead a situation in which the climate-related commitments of the different countries are actually enacted. The NZE scenario represents the situation in which the global temperature rise has to be mitigated to 1.5 °C above pre-industrial levels by the year 2100. The total costs of the supply chain for the base case scenario resulted to be 65.17 M€/year, while for STEPS, APS and NZE scenarios respectively it resulted to be 142, 163 and 161 M€/year. The APS scenario was the one characterized by the highest costs, having the largest quantity of waste EV lithium batteries, which specific processing and transport costs are higher than the other technologies. The main findings of the study identified optimal locations for recycling facilities of specific sizes to minimise total supply chain costs. For the waste EV lithium batteries, apart from the base case scenario, it resulted to be more economically convenient to install one single large recycling plant for the whole country, in order to benefit from economies of scales effect, that allows to reduce the processing costs. Similarly, for PV panels, fewer larger facilities were more cost-effective, particularly with two central locations selected for most scenarios. For the waste NdFeB permanent magnets, the situation changed, since the total quantity of materials available is limited, for all the scenarios, with respect to the other technologies. Thus, the effect of the economies of scale is not significant enough, to cover the increase in transport expenses, when only one or two locations are selected. Comparisons between the total supply chain costs and market prices of virgin CRM revealed that costs attributed to each element were generally lower than market prices, indicating the potential economic feasibility of CRM recycling. However, this comparison requires further refinement to assess economic viability more accurately. The main limitation of this supply chain model lies in estimating processing costs. Due to the limited technical data available in the literature, certain assumptions have been necessary, which may impact the accuracy of cost calculations. Moreover, the processing costs for the different recycling techniques are obtained from different papers and reports, so different assumptions, methods and levels of accuracy might have been used in the techno-economical calculations, done by the different authors. In conclusion, this thesis optimised the CRM supply chain from an economic point of view. Future works should instead address also the environmental performances of the supply chain and perform a multiple objective optimisation, considering economic ad environmental performance of the supply chain. An important consideration for the future advancement of the supply chain model involves incorporating the option of transporting the CRM utilising the Italian rail system. Additionally, expanding the geographical boundaries of the model to encompass all EU countries could enhance its comprehensiveness.

Furthermore, the future development of this work should entail a more precise cost estimation for the recycling processes. This meticulous approach will ensure a comprehensive evaluation of the economic viability and sustainability of the supply chain optimisation efforts.

Appendix

A.1 Availability from recycle

In Tables A.1, A.2, A.3 the quantities of the different waste materials, for each province, are reported, along with the coordinates, in radians, of all the Italian provinces.

Table A.1. *Coordinates and availability of waste materials for each province for the STEPS scenario [t/year]*

	Lat [rad]	Long [rad]	Total PV	Total BATT	Total MAG
Alessandria	0.784	0.150	2459	71	0.43
Asti	0.784	0.143	850	36	0.22
Biella	0.795	0.141	867	33	0.20
Cuneo	0.775	0.132	5313	146	1.55
Novara	0.793	0.150	1026	88	0.54
Torino	0.787	0.134	4269	686	4.16
Verbania	0.802	0.149	186	30	0.18
Vercelli	0.791	0.147	834	37	0.22
Aosta	0.798	0.128	233	214	1.43
Bergamo	0.798	0.169	3236	349	2.12
Brescia	0.795	0.178	4916	440	2.67
Como	0.800	0.159	993	227	1.37
Cremona	0.788	0.175	2319	94	0.57
Lecco	0.800	0.164	543	115	0.70
Lodi	0.791	0.166	1218	49	0.30
Mantova	0.788	0.188	2270	98	0.59
Milano	0.794	0.160	3463	979	5.93
MonzaBrianza	0.796	0.162	1128	273	1.65
Pavia	0.789	0.160	1800	93	0.57
Sondrio	0.806	0.172	507	52	0.32
Varese	0.800	0.154	1522	286	1.73
Bolzano	0.812	0.198	2364	579	3.51
Trento	0.804	0.194	1830	2456	14.89

Belluno	0.805	0.213	468	28	0.17
Padova	0.792	0.207	3522	266	1.61
Rovigo	0.787	0.206	2926	32	0.20
Treviso	0.797	0.214	3549	258	1.57
Venezia	0.793	0.215	2061	175	1.06
Verona	0.793	0.192	3799	320	2.44
Vicenza	0.795	0.202	3118	296	1.79
Gorizia	0.802	0.238	400	28	0.17
Pordenone	0.802	0.221	1616	68	0.41
Trieste	0.797	0.240	281	41	0.25
Udine	0.804	0.231	2916	152	0.92
Genova	0.775	0.156	290	113	0.84
Imperia	0.766	0.140	268	24	0.15
LaSpezia	0.770	0.172	248	39	0.24
Savona	0.773	0.148	311	37	0.49
Bologna	0.777	0.198	3359	281	2.57
Ferrara	0.783	0.203	1844	49	0.29
Forli	0.772	0.210	2189	77	0.46
Modena	0.779	0.191	2693	179	1.09
Parma	0.782	0.180	1905	94	1.91
Piacenza	0.786	0.169	1808	50	0.31
Ravenna	0.775	0.213	3593	88	0.53
ReggioEmilia	0.780	0.186	1724	150	0.91
Rimini	0.769	0.219	912	66	0.40
Arezzo	0.759	0.207	1607	50	0.40
Firenze	0.764	0.196	1125	951	6.48
Grosseto	0.747	0.194	775	25	1.21
Livorno	0.760	0.180	730	39	4.25
Lucca	0.765	0.184	685	75	0.45
MassaCarrara	0.769	0.177	245	27	0.69
Pisa	0.763	0.182	964	66	6.34
Pistoia	0.767	0.191	416	48	0.29
Prato	0.766	0.194	747	44	0.27
Siena	0.756	0.198	718	41	0.25
Perugia	0.752	0.216	3300	113	0.76
Terni	0.743	0.221	1225	29	0.18
Ancona	0.761	0.236	2826	82	0.50
AscoliPiceno	0.748	0.237	1127	39	0.24
Fermo	0.753	0.239	993	27	0.16
Macerata	0.756	0.235	2851	55	0.87
PesaroUrbino	0.766	0.225	2347	67	1.73

Frosinone	0.727	0.233	1686	58	1.69
Latina	0.724	0.225	2421	77	0.47
Rieti	0.740	0.224	266	18	0.11
Roma	0.731	0.218	4534	1409	8.54
Viterbo	0.740	0.211	4290	38	2.46
Chieti	0.739	0.247	2144	45	5.79
LAquila	0.739	0.234	1559	39	2.31
Pescara	0.741	0.248	852	46	0.45
Teramo	0.745	0.239	2272	45	0.27
Campobasso	0.725	0.256	1224	16	13.78
Isernia	0.726	0.249	370	5	4.64
Avellino	0.714	0.258	837	27	8.02
Benevento	0.718	0.258	631	20	6.70
Caserta	0.717	0.250	2481	80	1.54
Napoli	0.713	0.249	1745	156	0.94
Salerno	0.710	0.258	2457	101	2.98
Bari	0.718	0.294	4709	117	0.71
Barletta	0.721	0.284	1583	19	1.81
Brindisi	0.709	0.313	4454	28	1.23
Foggia	0.724	0.271	5541	25	8.37
Lecce	0.704	0.317	6336	70	2.38
Taranto	0.706	0.301	3384	39	1.83
Matera	0.710	0.290	1674	21	3.17
Potenza	0.709	0.276	1752	29	5.97
Catanzaro	0.679	0.290	1282	29	5.59
Cosenza	0.686	0.284	2334	53	2.66
Crotone	0.682	0.299	356	4	13.18
ReggioCalabria	0.665	0.273	696	28	0.17
ViboValentia	0.675	0.281	386	6	0.04
Agrigento	0.651	0.237	2089	17	5.68
Caltanissetta	0.654	0.245	877	11	0.06
Catania	0.655	0.263	2196	122	0.74
Enna	0.656	0.249	685	7	5.19
Messina	0.667	0.271	683	49	0.30
Palermo	0.665	0.233	1716	85	16.96
Ragusa	0.644	0.257	1996	42	0.25
Siracusa	0.647	0.267	1888	42	4.08
Trapani	0.664	0.218	1470	28	3.46
Cagliari	0.684	0.159	2235	80	4.20
Nuoro	0.704	0.163	1305	24	6.62
Oristano	0.696	0.150	1275	18	2.70

Sassari	0.711	0.149	2203	64	18.04
SudSardegna	0.684	0.149	1814	30	6.11
Total			**199314**	**15392**	**274**

Table A.2. *Coordinates and availability of waste materials for each province for the APS scenario [t/year]*

	Lat [rad]	Long [rad]	Total PV	Total BATT	Total MAG
Alessandria	0.784	0.150	3146	72	0.44
Asti	0.784	0.143	1088	37	0.22
Biella	0.795	0.141	1110	33	0.20
Cuneo	0.775	0.132	6798	148	1.79
Novara	0.793	0.150	1313	90	0.54
Torino	0.787	0.134	5462	695	4.21
Verbania	0.802	0.149	238	30	0.18
Vercelli	0.791	0.147	1067	37	0.23
Aosta	0.798	0.128	298	217	1.49
Bergamo	0.798	0.169	4140	353	2.14
Brescia	0.795	0.178	6290	446	2.70
Como	0.800	0.159	1271	230	1.39
Cremona	0.788	0.175	2967	95	0.58
Lecco	0.800	0.164	695	117	0.71
Lodi	0.791	0.166	1559	50	0.30
Mantova	0.788	0.188	2904	99	0.60
Milano	0.794	0.160	4431	991	6.01
MonzaBrianza	0.796	0.162	1444	276	1.67
Pavia	0.789	0.160	2304	94	0.57
Sondrio	0.806	0.172	649	53	0.32
Varese	0.800	0.154	1947	289	1.75
Bolzano	0.812	0.198	3025	586	3.55
Trento	0.804	0.194	2341	2487	15.07
Belluno	0.805	0.213	598	28	0.17
Padova	0.792	0.207	4506	269	1.63
Rovigo	0.787	0.206	3744	33	0.20
Treviso	0.797	0.214	4541	262	1.59
Venezia	0.793	0.215	2637	177	1.07
Verona	0.793	0.192	4861	324	2.63
Vicenza	0.795	0.202	3990	299	1.81
Gorizia	0.802	0.238	512	28	0.17
Pordenone	0.802	0.221	2068	69	0.42
Trieste	0.797	0.240	360	41	0.25

Udine	0.804	0.231	3731	154	0.94
Genova	0.775	0.156	371	114	0.90
Imperia	0.766	0.140	343	25	0.15
LaSpezia	0.770	0.172	317	40	0.24
Savona	0.773	0.148	397	37	0.58
Bologna	0.777	0.198	4298	285	2.88
Ferrara	0.783	0.203	2359	49	0.30
Forli	0.772	0.210	2801	77	0.47
Modena	0.779	0.191	3446	182	1.10
Parma	0.782	0.180	2437	95	2.37
Piacenza	0.786	0.169	2313	51	0.31
Ravenna	0.775	0.213	4597	89	0.54
ReggioEmilia	0.780	0.186	2205	152	0.92
Rimini	0.769	0.219	1167	67	0.40
Arezzo	0.759	0.207	2056	51	0.44
Firenze	0.764	0.196	1439	963	6.80
Grosseto	0.747	0.194	991	25	1.58
Livorno	0.760	0.180	933	40	5.61
Lucca	0.765	0.184	876	76	0.46
MassaCarrara	0.769	0.177	314	27	0.88
Pisa	0.763	0.182	1234	67	8.35
Pistoia	0.767	0.191	533	48	0.29
Prato	0.766	0.194	956	44	0.27
Siena	0.756	0.198	919	42	0.25
Perugia	0.752	0.216	4222	114	0.80
Terni	0.743	0.221	1568	29	0.18
Ancona	0.761	0.236	3615	83	0.50
AscoliPiceno	0.748	0.237	1441	39	0.24
Fermo	0.753	0.239	1271	27	0.17
Macerata	0.756	0.235	3648	56	1.05
PesaroUrbino	0.766	0.225	3002	68	2.19
Frosinone	0.727	0.233	2157	59	2.15
Latina	0.724	0.225	3098	78	0.48
Rieti	0.740	0.224	341	18	0.11
Roma	0.731	0.218	5801	1426	8.65
Viterbo	0.740	0.211	5489	38	3.21
Chieti	0.739	0.247	2743	46	7.67
LAquila	0.739	0.234	1994	40	3.01
Pescara	0.741	0.248	1090	47	0.51
Teramo	0.745	0.239	2908	46	0.28
Campobasso	0.725	0.256	1567	17	18.42

Isernia	0.726	0.249	473	6	6.20
Avellino	0.714	0.258	1071	28	10.68
Benevento	0.718	0.258	807	20	8.93
Caserta	0.717	0.250	3174	81	1.91
Napoli	0.713	0.249	2233	158	0.95
Salerno	0.710	0.258	3143	103	3.78
Bari	0.718	0.294	6025	119	0.72
Barletta	0.721	0.284	2026	20	2.39
Brindisi	0.709	0.313	5699	29	1.59
Foggia	0.724	0.271	7089	25	11.15
Lecce	0.704	0.317	8107	71	3.05
Taranto	0.706	0.301	4330	39	2.37
Matera	0.710	0.290	2142	22	4.20
Potenza	0.709	0.276	2242	30	7.93
Catanzaro	0.679	0.290	1640	29	7.42
Cosenza	0.686	0.284	2987	54	3.45
Crotone	0.682	0.299	456	4	17.64
ReggioCalabria	0.665	0.273	891	29	0.17
ViboValentia	0.675	0.281	494	6	0.04
Agrigento	0.651	0.237	2673	18	7.56
Caltanissetta	0.654	0.245	1122	11	0.07
Catania	0.655	0.263	2809	124	0.75
Enna	0.656	0.249	876	7	6.94
Messina	0.667	0.271	874	50	0.30
Palermo	0.665	0.233	2195	86	22.54
Ragusa	0.644	0.257	2554	42	0.26
Siracusa	0.647	0.267	2415	43	5.37
Trapani	0.664	0.218	1880	28	4.57
Cagliari	0.684	0.159	2860	81	5.46
Nuoro	0.704	0.163	1669	24	8.81
Oristano	0.696	0.150	1631	18	3.58
Sassari	0.711	0.149	2818	65	24.03
SudSardegna	0.684	0.149	2321	30	8.12
Total			**255019**	**15583**	**336**

Table A.3. *Coordinates and availability of waste materials for each province for the NZE scenario [t/year]*

	Lat [rad]	**Long [rad]**	**Total PV**	**Total BATT**	**Total MAG**
Alessandria	0.784	0.150	3157	69	0.419
Asti	0.784	0.143	1092	35	0.214

Biella	0.795	0.141	1113	32	0.194
Cuneo	0.775	0.132	6822	142	1.851
Novara	0.793	0.150	1317	86	0.521
Torino	0.787	0.134	5481	667	4.043
Verbania	0.802	0.149	239	29	0.177
Vercelli	0.791	0.147	1070	36	0.218
Aosta	0.798	0.128	299	208	1.462
Bergamo	0.798	0.169	4155	339	2.057
Brescia	0.795	0.178	6313	428	2.593
Como	0.800	0.159	1275	220	1.336
Cremona	0.788	0.175	2978	92	0.555
Lecco	0.800	0.164	698	112	0.679
Lodi	0.791	0.166	1564	48	0.288
Mantova	0.788	0.188	2914	95	0.575
Milano	0.794	0.160	4447	952	5.769
MonzaBrianza	0.796	0.162	1449	265	1.608
Pavia	0.789	0.160	2312	91	0.549
Sondrio	0.806	0.172	651	51	0.308
Varese	0.800	0.154	1954	278	1.683
Bolzano	0.812	0.198	3036	563	3.409
Trento	0.804	0.194	2349	2388	14.471
Belluno	0.805	0.213	600	27	0.163
Padova	0.792	0.207	4522	258	1.566
Rovigo	0.787	0.206	3757	32	0.191
Treviso	0.797	0.214	4557	251	1.523
Venezia	0.793	0.215	2646	170	1.031
Verona	0.793	0.192	4879	311	2.626
Vicenza	0.795	0.202	4004	287	1.742
Gorizia	0.802	0.238	514	27	0.164
Pordenone	0.802	0.221	2075	66	0.402
Trieste	0.797	0.240	361	40	0.240
Udine	0.804	0.231	3745	148	0.898
Genova	0.775	0.156	373	109	0.900
Imperia	0.766	0.140	344	24	0.143
LaSpezia	0.770	0.172	318	38	0.232
Savona	0.773	0.148	399	36	0.613
Bologna	0.777	0.198	4313	273	2.946
Ferrara	0.783	0.203	2367	47	0.286
Forli	0.772	0.210	2811	74	0.451
Modena	0.779	0.191	3458	174	1.056
Parma	0.782	0.180	2446	92	2.549

Piacenza	0.786	0.169	2321	49	0.297
Ravenna	0.775	0.213	4614	85	0.517
ReggioEmilia	0.780	0.186	2213	146	0.883
Rimini	0.769	0.219	1171	64	0.388
Arezzo	0.759	0.207	2064	49	0.438
Firenze	0.764	0.196	1444	924	6.678
Grosseto	0.747	0.194	995	24	1.730
Livorno	0.760	0.180	937	38	6.212
Lucca	0.765	0.184	879	73	0.442
MassaCarrara	0.769	0.177	315	26	0.950
Pisa	0.763	0.182	1238	65	9.239
Pistoia	0.767	0.191	535	46	0.280
Prato	0.766	0.194	959	43	0.259
Siena	0.756	0.198	922	40	0.244
Perugia	0.752	0.216	4237	109	0.782
Terni	0.743	0.221	1573	28	0.171
Ancona	0.761	0.236	3628	80	0.482
AscoliPiceno	0.748	0.237	1446	38	0.229
Fermo	0.753	0.239	1275	26	0.160
Macerata	0.756	0.235	3661	54	1.118
PesaroUrbino	0.766	0.225	3013	65	2.372
Frosinone	0.727	0.233	2165	57	2.336
Latina	0.724	0.225	3109	75	0.456
Rieti	0.740	0.224	342	17	0.104
Roma	0.731	0.218	5822	1370	8.301
Viterbo	0.740	0.211	5508	37	3.544
Chieti	0.739	0.247	2752	44	8.496
LAquila	0.739	0.234	2001	38	3.313
Pescara	0.741	0.248	1094	45	0.525
Teramo	0.745	0.239	2918	44	0.266
Campobasso	0.725	0.256	1572	16	20.497
Isernia	0.726	0.249	475	5	6.894
Avellino	0.714	0.258	1075	26	11.868
Benevento	0.718	0.258	810	20	9.927
Caserta	0.717	0.250	3185	77	2.051
Napoli	0.713	0.249	2240	151	0.917
Salerno	0.710	0.258	3155	99	4.118
Bari	0.718	0.294	6046	114	0.691
Barletta	0.721	0.284	2033	19	2.645
Brindisi	0.709	0.313	5719	27	1.748
Foggia	0.724	0.271	7115	24	12.398

Lecce	0.704	0.317	8136	68	3.331
Taranto	0.706	0.301	4345	38	2.600
Matera	0.710	0.290	2150	21	4.658
Potenza	0.709	0.276	2250	28	8.802
Catanzaro	0.679	0.290	1646	28	8.238
Cosenza	0.686	0.284	2997	52	3.795
Crotone	0.682	0.299	458	4	19.640
ReggioCalabria	0.665	0.273	894	27	0.166
ViboValentia	0.675	0.281	496	6	0.036
Agrigento	0.651	0.237	2682	17	8.408
Caltanissetta	0.654	0.245	1126	10	0.063
Catania	0.655	0.263	2819	119	0.721
Enna	0.656	0.249	879	7	7.716
Messina	0.667	0.271	877	48	0.290
Palermo	0.665	0.233	2203	83	25.023
Ragusa	0.644	0.257	2563	41	0.246
Siracusa	0.647	0.267	2424	41	5.945
Trapani	0.664	0.218	1887	27	5.067
Cagliari	0.684	0.159	2870	78	6.008
Nuoro	0.704	0.163	1675	23	9.790
Oristano	0.696	0.150	1637	17	3.972
Sassari	0.711	0.149	2828	63	26.700
SudSardegna	0.684	0.149	2329	29	9.020
Total			**255925**	**14962**	**360**

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