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Environmental Assessment of Global Magnesium Production

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Concerns about climate change call for a careful assessment of the environmental impact of the supply chain of critical materials such as magnesium (Mg) which has a broad range of applications. Enhancing the circularity of this material is vital for ensuring its sustainable use. However, systematic analysis of the sustainability of the global production of magnesium and its circularity is still missing. We propose a novel dynamic model based on geology and processing routes to quantify the key environmental concerns across the life cycle of primary and secondary magnesium. Energy consumption, water use and related emissions are assessed for recycling including functional (recovered Mg reused in the closed-loop supply chain) and non-functional (recovered Mg as an element used in aluminum alloys as open-loop supply chain), as well as casting and molding. Results show a significant potential contribution of circularity of magnesium to energy (up to 31 billion GJ) and water (up to 2.7 Km^3) savings, as well as the mitigation of greenhouse gas (GHG) emissions (up to 3 billion tonnes CO_2 eq), globally. However, the analysis indicates that 87% of secondary magnesium comes from non-functional recycling. The result shows the possible increase of non-functional recycling of magnesium from 612 kt in 2020 to 1 mt in 2050, and the growth of functional recycling of magnesium from 96 kt in 2020 to 161 kt in 2050. The finding highlights the necessity for improving supply chain policies of Mg through technological developments and operational changes to ensure its sustainable circular economy.

Keywords: Magnesium; Critical material; Circular economy; Environmental sustainability; Dynamics modelling

1. Introduction

Magnesium (Mg) is an alkaline earth metal with the most common +2 oxidation state. World resources of magnesium are enormous. Magnesium is the third most abundant element in seawater; on average, a cubic kilometer of seawater contains 1250 tons of magnesium (Al Mutaz and

Wagialia 1990) (composition of seawater and brines are provided in Appendix Table A1). Also, magnesium is the eighth most abundant element in the Earth's crust, representing approximately 2.1% of its composition (Prasad *et al.* 2021) and constitutes 13% of the planet's mass (Navarra *et al.* 2021).

As the lightest structural metal, magnesium is considered one of the most relevant strategic materials for products where lightweight design is needed, e.g., for low greenhouse gas (GHG) emitting technologies. The global demand for magnesium alloys has been rapidly increasing for technical and engineering applications. Moreover, there is a rapidly growing demand for magnesium compounds, e.g., magnesia, magnesium chloride, magnesium hydroxide and magnesium sulfates. For instance, the demand for magnesium sulfate has increased in agricultural applications and consumption of caustic-calcined magnesia has continued to increase for animal feed supplements and fertilizers as the importance of magnesium as a nutrient gained recognition (Navarra *et al.* 2021). Metallic Mg is used mostly in the automotive industry (44%) to decrease vehicle weight in response to consumer desires for increased fuel efficiency (Kharitonov *et al.* 2021). For example, the European Parliament adopted a stringent Regulation on CO_2 emissions in the automotive sector (EU Regulation 443/2009) setting the target of 10 g CO_2/km in 2050 (Türe and Türe 2020). Besides the automotive industry, magnesium is applied mainly in packaging (19%), construction (12%), desulfurization (11%), transportation, including air transport, maritime and railway transport (4%), and other industries (10%).

Looking from the supply side, China is considered the leading global supplier of magnesium, with the production of approximately 970 kt of metal and 19,000 kt of Mg compounds in 2019 (Kramer 2000). Other top producers of metallic magnesium from primary sources are Russia (67 kt), Kazakhstan (25 kt), Brazil (22 kt), Israel (21 kt), Ukraine (8 kt), Turkey (7 kt), and

Iran (1 kt) (Kramer 2000). In the mining stage, magnesium is found in over 60 minerals. The primary sources of the most important magnesium minerals and theoretical Mg content are shown in Table 1.

Table 1. Main sources of magnesium minerals.

Type of Mg source	**Wt.%, Mg (theoretical Mg content)**	**Formula**	**Ref**
Carnallite	8.7	$KMgCl_3 \cdot 6H_2O$	(Prasad *et al.* 2021)
Magnesite	47.6	$MgCO_3$	(Kramer 2000)
Dolomite	22.0	$CaCO_3 \cdot MgCO_3$	(Kramer 2000)
Brucite	69.0	$Mg(OH)_2$	(Kramer 2000)
Olivine	19.0	$Mg_2Fe_2SiO_4$	(Kramer 2000)
Bischofite	11.9	$MgCl_2 \cdot 6H_2O$	(Harraz 2017)

Despite widespread and unlimited Mg sources, magnesium was designated a critical material by the EU Commission in 2017 due to the absence of primary production in Europe, e.g., Norway stopped producing the mineral because they were unable to compete with lower costs of Chinese producers. The supply of Mg for the manufacturing industry in the EU entirely relies on imports from China and a few other non-EU countries (Israel, Russia, and Turkey), while 15% of the global Mg consumption corresponds to the EU. China ordered to close roughly 35 of its 50 magnesium smelters at the end of 2021. There are two main reasons for shutting down more than half of Chinese installations that produce Mg. On one side, the energy cost of magnesium production is very high, e.g., about 4kg of coal is needed to produce 1kg of magnesium (Gonçalves *et al.* 2022). Besides high energy intensity of Mg production, new regulations published by the Development and Reform Commission (DRC), Yulin City in 2021 are considered to reduce emissions and consumption targets. Such changing policies significantly affect the supply of Mg to the European stocks and considerably increase the criticality of this metal. Given difficulties involved in storing Mg which starts to oxidize after three months, global stocks could run critically low. Therefore, policy changes in China directly affect prices and availability of all grades of magnesia in the world. For example, the price of Mg, which in recent years oscillated around \$2,000 per tonne, raised to more than \$11,000 in September 2021.

One of the solutions to these problems lies in improving the circularity of magnesium by recycling and developing ways to use it more efficiently (Cisternas *et al.* 2021). The concept of circular economy has emerged to sustain the conservation of the material within the supply chain (El Wali *et al.* 2021). Circular economy principles intend to improve the supply of materials from secondary sources while contributing to solving the political problem of Mg shortage and reducing energy consumption and energy-related emissions compared to primary production (Rahimpour Golroudbary *et al.* 2020). This concept serves the mitigation of magnesium criticality, as it aims to extend the useful life of raw materials extracted from the environment. There are several studies devoted to recycling of end-of-life scrap containing magnesium and recovery of Mg as secondary alloy, however, those analyses are based on specific industrial cases, e.g, (Cherubini *et al.* 2008, Bell *et al.* 2015) environmental assessment focused on the automotive industry (Tharumarajah and Koltun 2007, Gonçalves *et al.* 2022) and on China (Shao *et al.* 2014). While the major focus in magnesium management is on replacing primary production with recycled material, environmental concerns of recycling activities such as demand for energy and water, as well as generating emissions are often overlooked (Rahimpour Golroudbary *et al.* 2019). Besides, there is a gap in literature on the holistic assessment of functional (recovered Mg reused in the closed-loop supply chain) and non-functional (recovered Mg reused in the open-loop supply chain) processing at the recycling stage as a center of the circular economy concept at a global scale. Therefore, the global magnesium production chain should be considered on a life cycle basis to evaluate its environmental impacts over all supply chain stages, from mining to recycling. Table 2 shows that our study is the first global analysis of the magnesium supply chain including all applications. Hence, the main objective of this paper is to present a novel dynamic model of the global supply chain of magnesium to perform environmental sustainability assessment for Mg recycling, including functional and non-functional processes in line with the circular economy concept. The novelty of this study consists in conducting a comprehensive assessment of the quantitative impact of functional and non-functional recycling of magnesium on sustainability of its supply chain. Therefore, this study attempts to assist in understanding to what extent functional and non-functional Mg recycling contributes to its sustainable production from an environmental perspective and evaluate dynamic changes through magnesium supply chain over time in the period 2000-2050. We provide a comparison of energy consumption, water use, and related emissions for primary and secondary magnesium based on the production method, geological and geographical features, and demonstrate that sustainability can be achieved by improving Mg recycling.

Table 2. Summary of investigation on the environmental impact of magnesium supply chain.

Reference	Objective of study	Methodology	Supply chain stages				Environmental impact			Case study	Geographical scope
			Mining	Processing	Manufacturing	Recycling	Energy	Water	Emissions		
(Hakamada *et al.* 2007)	Life cycle inventory study on magnesium alloy substitution in vehicles	LCA		×	×	×	×		×	Automotive industry	Region is not specified
(GAO *et al.* 2008)	Assessing environmental impact of magnesium production	LCA	×				×		×	Pidgeon process	Local: China
(Du *et al.* 2010)	Life cycle assessment of automobiles using magnesium from Chinese Pidgeon process	LCA	×	×	×	×	×		×	Automotive industry	Local: China

(Witik *et al.* 2011)	Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications	LCA and scenarios	×	×	×	×	×	Automotive industry	Region is not specified
(Ehrenberger and Friedrich 2013)	Evaluation of the environmental effects of using magnesium in the aluminum cycle	LCA		×	×		×	Automotive industry	Region is not specified
(Türe and Türe 2020)	Assessment of using magnesium on CO_2 emissions	Experimental and calculation		×			×	Automotive industry	Regional: Europe
(Bautista *et al.* 2021)	Life cycle assessment of	LCA and scenarios		×			×	Battery industry	Region is not specified

	magnesium battery										
(Rahimpour Golroudbary *et al.* 2022)	Magnesium Life Cycle in Automotive Industry	System dynamics modelling integrated with LCA	×	×	×	×	×	×	×	Automotive industry	Regional: Europe
Current study	Global environmental impact of magnesium suuply chain	System dynamics modelling integrated with LCA and geometallurgical approach	×	×	×	×	×	×	×	All industries including semi-finished and finished products	Global

2. Materials and Method

In this study, the United States Geological Survey (USGS) (Ober 2020), European Commission (Blengini et al. 2020), GREET-2020 software (Wang et al. 2020), Statista database (Gullen and Plungis 2021), and other studies (Rahimpour Golroudbary et al. 2019, 2020, Golroudbary et al. 2022) are used as the primary data sources. Figure A1 in Appendix provides details of model and data used. We develop a novel dynamic model based on the system dynamics (SD) methodology introduced by Forrester (Forrester 1997) by integrating the life cycle assessment and geo-metallurgical approach. The significance of this combination lies in the ability to quantify mass flows and assess environmental consequences within a holistic system considering the dynamic behavior and interaction of multiple parameters of the global magnesium supply chain over time. This type of dynamic modeling creates a bridge between mass flow analysis and environmental assessment as it allows researchers from both fields to tackle new research questions with unique comprehensiveness. Figure 1 shows details of the model of magnesium supply chain focusing on mass flows and its environmental concerns. The proposed model consists of global magnesium flows, the respective energy and water consumption and related emissions. The model is composed of three main parts: (i) extractive stage which includes mining of magnesium and processing metal and its alloys, as well as casting & molding of primary magnesium (ii) production stage which includes manufacturing of semi-finished and final products, (iii) recycling stage which includes functional and non-functional processes as well as casting and molding of secondary magnesium.

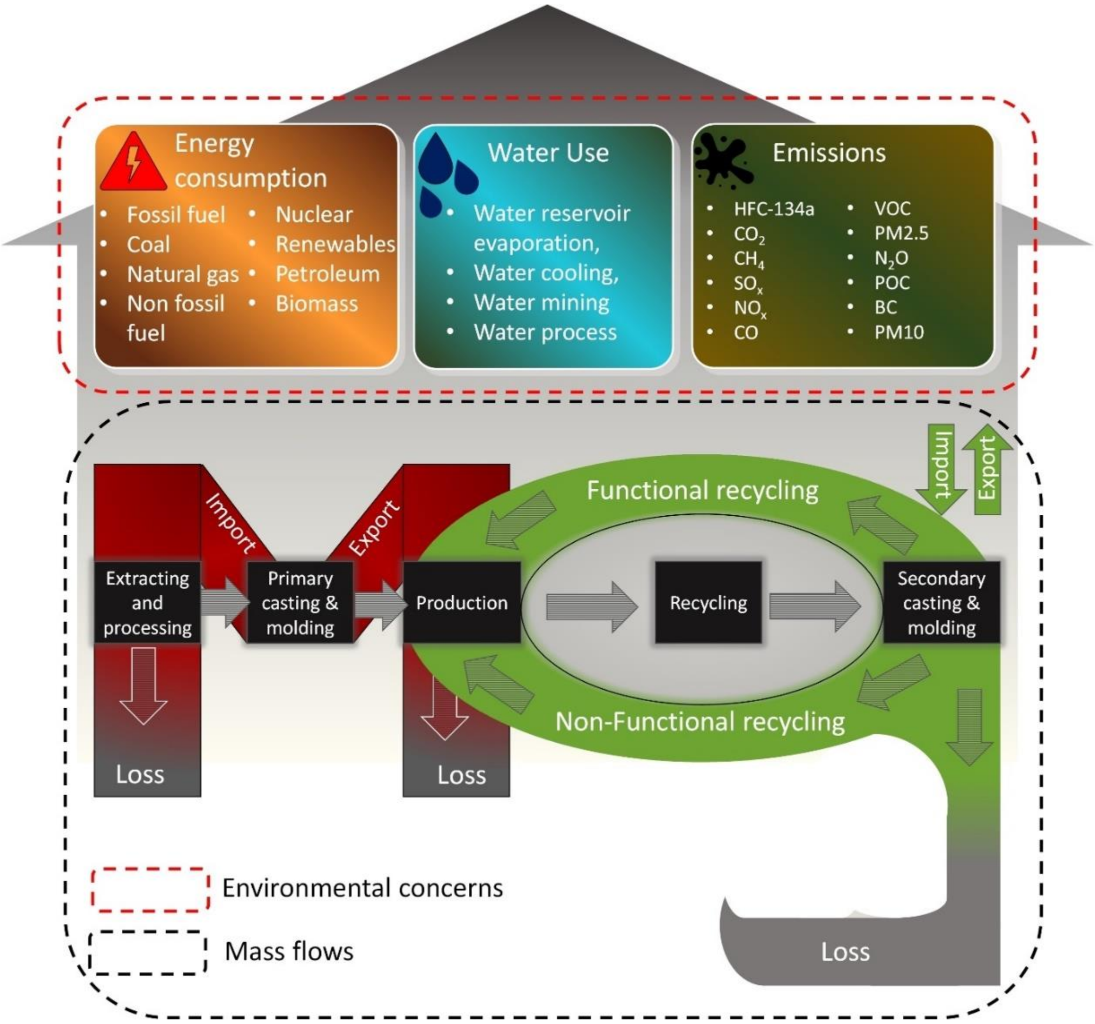

Figure 1. Conceptual framework of the proposed model of magnesium supply chain.

We divided the variables of the dynamic model into two groups, including endogenous and exogenous variables to specify model boundaries. Endogenous variables affect and are affected by other system components and parameters, while exogenous variables are not directly affected by the system. The group and type of all variables are specified in Table for mass flow, Table 4 for energy flow, Table 5 for water flow and Table 6 for energy-related emissions.

Table 3. Description of variables of the proposed dynamic model for mass flow in the magnesium supply chain.

Variable	Term	Type of variable	Group
$\boldsymbol{A(t)}$	Global stock of primary magnesium	Stock	Endogenous
$\boldsymbol{M(t)}$	Global annual rate of extracted magnesium	Flow	Endogenous

Variable	Term	Type of variable	Group
$\boldsymbol{f_i(t)}$	Global processing rate of magnesium ‘*i*’[1]	Auxiliary	Endogenous
$\boldsymbol{r_i}$	Conversion factor for each process in mining ‘*i*’[1]	Auxiliary	Endogenous
$\boldsymbol{N(t)}$	Global annual production rate of magnesium	Flow	Endogenous
$\boldsymbol{k_j(t)}$	Global annual production rate of magnesium ‘*j*’[2]	Auxiliary	Endogenous
$\boldsymbol{q_j}$	Conversion factor for each flow in processing stage ‘*j*’[2]	Auxiliary	Endogenous
$\boldsymbol{B(t)}$	Cumulative amount of Mg used in manufactured semi-finished products	Stock	Endogenous
$\boldsymbol{O(t)}$	Global annual amount of Mg used in semi-finished products ‘*k*’[3]	Flow	Endogenous
$\boldsymbol{\delta_k}$	Coefficient of global magnesium used in industry ‘*k*’[3]	Auxiliary	Exogenous
$\boldsymbol{C(t)}$	Cumulative amount of Mg used in manufactured finished products	Stock	Endogenous
$\boldsymbol{P(t)}$	Global annual amount of Mg used in finished products ‘*m*’[4]	Flow	Endogenous
$\boldsymbol{\upsilon_l}$	Coefficient of global magnesium used in industry ‘*m*’[4]	Auxiliary	Exogenous
$\boldsymbol{D(t)}$	Cumulative amount of Mg available in collected end-of-life products	Stock	Endogenous
$\boldsymbol{L(t)}$	Global annual amount of Mg available in collected end-of-life products ‘*n*’[5]	Flow	Endogenous
$\boldsymbol{\varphi_f}$	Coefficient of global magnesium collected from industry ‘*n*’[5]	Auxiliary	Exogenous
$\boldsymbol{E(t)}$	Cumulative amount of functionally recycled Mg	Stock	Endogenous
$\boldsymbol{Q(t)}$	Global annual amount of functionally recycled Mg from sector ‘*g*’ (*g=1,2*) including transportation, and iron & steel	Flow	Endogenous
$\boldsymbol{\varrho_g}$	Coefficient of global functional recycling of magnesium from sector ‘*g*’ (*g=1,2*) including transportation, and iron & steel	Auxiliary	Exogenous
$\boldsymbol{F(t)}$	Cumulative amount of non-functionally recycled Mg	Stock	Endogenous
$\boldsymbol{R(t)}$	Global annual amount of non-functionally recycled Mg from sector ‘*h*’ (*h=1,2,3*) including transportation, packaging, and construction	Flow	Endogenous
$\boldsymbol{\mathcal{E}_h}$	Coefficient of global non-functional recycling of magnesium from sector ‘*h*’ (*h=1,2,3*) including transportation, packaging, and construction	Auxiliary	Exogenous
$\boldsymbol{G(t)}$	Cumulative amount of casting & molding of functionally recycled Mg	Stock	Endogenous
$\boldsymbol{CQ(t)}$	Global annual amount of casting & molding of functionally recycled Mg from sector ‘*g*’[6]	Flow	Endogenous
$\boldsymbol{y_g}$	Coefficient of casting & molding of magnesium through global functional recycling from sector ‘*g*’[6]	Auxiliary	Exogenous
$\boldsymbol{H(t)}$	Cumulative amount of casting & molding of non-functionally recycled Mg	Stock	Endogenous
$\boldsymbol{CR(t)}$	Global annual amount of casting & molding of non-functionally recycled Mg from sector ‘*h*’[7]	Flow	Endogenous
$\boldsymbol{z_h}$	Coefficient of casting & molding of magnesium through global non-functional recycling from sector ‘*h*’[7]	Auxiliary	Exogenous

[1] Type of process in mining ‘*i*’ (*i=1,2*): minerals and seawater or brines.

[2] Type of production ‘*j*’ (*j=1,2*): metallic magnesium and Mg alloys.

[3] Type of semi-finished products ‘*k*’ (*k=1,2,…,6*): die castings, nodular cast iron, manufacturing of iron and steel, titanium refining, aluminum alloys and other industries

[4] Type of finished products ‘*m*’ (*m=1,2,…,5*): vehicle, aircraft, packaging, construction, and desulfurization agent industry

[5] Type of end of life products ‘*n*’ (*n=1,2,…,5*): vehicle, aircraft, packaging, construction, and iron & steel

[6] Type of functional recycling sector ‘*g*’ (*g=1,2*): transportation and iron & steel

[7] Type of non-functional recycling sector ‘*h*’ (*h=1,2,3*): transportation, packaging, and construction

Table 4. Description of variables of the proposed dynamic model for energy consumption in the magnesium supply chain.

Type of production	Variable	Term	Type of variable	Group
Primary production of magnesium	$\boldsymbol{\lambda_{fl}}$	Energy consumption coefficient for process ‘f’[1] from sources of energy ‘l’[2]	Auxiliary	Exogenous
	$\boldsymbol{EG\ (t)}$	Annual rate of energy consumption during process ‘f’[1] from sources of energy ‘l’[2]	Flow	Endogenous
	$\boldsymbol{EH\ (t)}$	Total energy consumption for process ‘f’[1] from sources of energy ‘l’[2]	Stock	Endogenous
	$\boldsymbol{\alpha_{l}}$	Energy consumption coefficient for casting and molding from sources of energy ‘l’[2]	Auxiliary	Exogenous
	$\boldsymbol{EI\ (t)}$	Annual rate of energy consumption for casting and molding from sources of energy ‘l’[2]	Flow	Endogenous
	$\boldsymbol{EJ\ (t)}$	Total energy consumption for casting and molding from sources of energy ‘l’[2]	Stock	Endogenous
Secondary production of magnesium	$\boldsymbol{\beta_{bl}}$	Energy consumption coefficient for recycling ‘b’[3] from sources of energy ‘l’[2]	Auxiliary	Exogenous
	$\boldsymbol{EK\ (t)}$	Annual rate of energy consumption for recycling ‘b’[3] from sources of energy ‘l’[2]	Flow	Endogenous
	$\boldsymbol{EL\ (t)}$	Total energy consumption for recycling ‘b’[3] from sources of energy ‘l’[2]	Stock	Endogenous
	$\boldsymbol{\omega_{bl}}$	Energy consumption coefficient for casting and molding during recycling ‘b’[3] from sources of energy ‘l’[2]	Auxiliary	Exogenous
	$\boldsymbol{ES\ (t)}$	Annual rate of energy consumption for casting and molding for recycling ‘b’[3] from sources of energy ‘l’[2]	Flow	Endogenous
	$\boldsymbol{ET\ (t)}$	Total energy consumption for casting and molding during recycling ‘b’[3] from sources of energy ‘l’[2]	Stock	Endogenous

[1] Type of process ‘f’ (f =1,2): electrolysis and thermal reduction

[2] The sources of energy ‘l’ (l =1,2,3,…,8): fossil fuel, natural gas, coal, non-fossil fuel, nuclear, renewables, petroleum, and biomass

[3] Type of recycling ‘b’ (b =1,2): functional and non-functional

Table 5. Description of variables of the proposed dynamic model for water use in magnesium supply chain.

Type of production	Variable	Term	Type of variable	Group
Primary production of magnesium	$\boldsymbol{\tau_{fr}}$	Water consumption coefficient for process ‘f’[1] from source ‘r’[2]	Auxiliary	Exogenous
	$\boldsymbol{WU\ (t)}$	Annual rate of water use for process ‘f’[1] from source ‘r’[2]	Flow	Endogenous
	$\boldsymbol{WV\ (t)}$	Total water use for the process ‘f’[1] by the/from source ‘r’[2]	Stock	Endogenous
	$\boldsymbol{\rho_{r}}$	Water use coefficient for casting and molding from source ‘r’[2]	Auxiliary	Exogenous
	$\boldsymbol{WX\ (t)}$	Annual rate of water use for casting and molding from source ‘r’[2]	Flow	Endogenous
	$\boldsymbol{WY(t)}$	Total water use for casting and molding from source ‘r’[2]	Stock	Endogenous
Secondar	$\boldsymbol{\eta_{br}}$	Water use coefficient for recycling ‘b’[3] from source ‘r’[2]	Auxiliary	Exogenous

Type of production	Variable	Term	Type of variable	Group
	$\boldsymbol{WZ\ (t)}$	Annual rate of water use for recycling ‘*b*’[3] from source ‘*r*’[2]	Flow	Endogenous
	$\boldsymbol{WA\ (t)}$	Total water use for recycling ‘*b*’[3] from source ‘*r*’[2]	Stock	Endogenous
	$\boldsymbol{\Psi_{br}}$	Water use coefficient for casting and molding through recycling ‘*b*’[3] from source ‘*r*’[2]	Auxiliary	Exogenous
	$\boldsymbol{WB\ (t)}$	Annual rate of water use for casting and molding for recycling ‘*b*’[3] by sources ‘*r*’[2]	Flow	Endogenous
	$\boldsymbol{WD\ (t)}$	Total water use for casting and molding for recycling ‘*b*’[3] from source ‘*r*’[2]	Stock	Endogenous

[1]The process ‘*f*’ (*f* =1,2): electrolysis and thermal reduction

[2]The sources ‘*r*’ (*r* =1,2,3,4): water reservoir evaporation, water cooling, water mining and water process

[3]Type of recycling ‘*b*’ (*b* =1,2): functional and non-functional

Table 6. Description of variables of the proposed dynamic model for emissions through the magnesium supply chain.

Type of production	Variable	Term	Type of variable	Group
Primary production of magnesium	$\boldsymbol{\varsigma_{fs}}$	Emission coefficient for process ‘*f*’[1] by the type of emissions ‘*s*’[2]	Auxiliary	Exogenous
	$\boldsymbol{GE(t)}$	Annual rate of emission for process ‘*f*’[1] by the type of emissions ‘*s*’[2]	Flow	Endogenous
	$\boldsymbol{GF(t)}$	Total emissions from process ‘*f*’[1] by the type of emissions ‘*s*’[2]	Stock	Endogenous
	$\boldsymbol{\chi_{s}}$	Emission coefficient for casting and molding by the type of emissions ‘*s*’[2]	Auxiliary	Exogenous
	$\boldsymbol{GH(t)}$	Annual rate of emission for casting and molding by the type of emissions ‘*s*’[2]	Flow	Endogenous
	$\boldsymbol{GL(t)}$	Total emissions from casting and molding by the type of emissions ‘*s*’[2]	Stock	Endogenous
Secondary production of magnesium	$\boldsymbol{\xi_{bs}}$	Emission coefficient for recycling ‘*b*’[3] by the type of emissions ‘*s*’[2]	Auxiliary	Exogenous
	$\boldsymbol{GM(t)}$	Annual rate of emissions for recycling ‘*b*’[3] by the type of emissions ‘*s*’[2]	Flow	Endogenous
	$\boldsymbol{GN(t)}$	Total water use for recycling ‘*b*’[3] by the type of emissions ‘*s*’[2]	Stock	Endogenous
	$\boldsymbol{\theta_{bs}}$	Emission coefficient for casting and molding for recycling ‘*b*’[3] by the type of emissions ‘*s*’[2]	Auxiliary	Exogenous
	$\boldsymbol{GO(t)}$	Annual rate of emissions for casting and molding for recycling ‘*b*’[3] by the type of emissions ‘*s*’[2]	Flow	Endogenous
	$\boldsymbol{GP(t)}$	Total emissions from casting and molding for recycling ‘*b*’[3] by the type of emissions ‘*s*’[2]	Stock	Endogenous

[1]The process ‘*f*’ (*f* =1,2): electrolysis and thermal reduction

[2]The type of emission ‘*s*’ (*s* =1,2,3,…,12): HFC-134a, carbon dioxide (CO_2), methane (CH_4), sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), particulate matter of a diameter smaller than 2.5 micrometer (PM2.5), nitrous oxide (N_2O), particulate organic carbon (POC), black carbon (BC), and airborne particulate matter smaller than 10 micrometer (PM10).

[3]Type of recycling ‘*b*’ (*b* =1,2): functional and non-functional

2.1 Extraction stage

In the extraction stage, mining includes production of primary magnesium extracted mainly from minerals such as dolomite, magnesite and carnallite (respectively 47%, 19% and 13% of magnesium oxide output), as well as seawater and brine (21% of global Mg) (Prasad *et al.* 2021). Primary Mg is principally used for casting in the automotive industry which accounts for 55% of its consumption. Aluminum-based alloys used in the same industry for similar applications account for 28%. The processing stage focuses on metallic magnesium and Mg alloys.

To quantify the stock and flow of the supply chain of magnesium, two types of equations including state and rate are considered in mathematical formulas. The state equations correspond to the calculation of the cumulative level of given inventory in the considered system. Therefore, it is based on the integration of net flows of stock in a given period ‘t_0-t’, where ‘t_0’ is the initial year and ‘t’ is the final year. The rate equations correspond to the calculation of input and output flows in the supply chain of magnesium.

Equation 1 corresponds to the cumulative amount of global primary magnesium in the mining stage in year t, $A(t)$. In Equation 2, $M(t)$ is the annual rate of extracted Mg, $f_i(t)$ is the rate of processing ‘i’ ($i=1,2$) including minerals and seawater or brines, r_i is the conversion factor of each process ‘i’ in mining. In Equation 3, $N(t)$ corresponds to the annual rate of magnesium production, $k_j(t)$ is the rate of production ‘j’ ($j=1,2$) including metallic Mg and Mg alloys, and q_j is the conversion factor of each production ‘j’ in the processing stage.

$$A(t) = \int_{t0}^{t}\big(M(t) - N(t)\big)dt + A(t_0) \qquad (1)$$

$$M(t) = \sum_{i=1}^{2} f_i(t) \times r_i \qquad (2)$$

$$N(t) = \sum_{n=1}^{2} k_j(t) \times q_j \qquad (3)$$

Magnesium metal is produced using two very different processes: thermal reduction and the electrolytic process. Figure 2 shows both flow diagrams for the production of metallic magnesium. The thermal reduction process uses a metallothermic reduction reaction in which silicon and/or aluminum extract magnesium as a vapor from the oxide. Magnesium oxide is usually provided in the form of calcined dolomite (MgO·CaO), sometimes enriched with calcined magnesite (MgO). The basic reaction is shown in Table 7. Since the reaction is highly endothermic, industrial processes operate under vacuum at lower temperatures in a batch mode to limit deterioration of construction materials and suppress undesirable side reactions in the gas system.

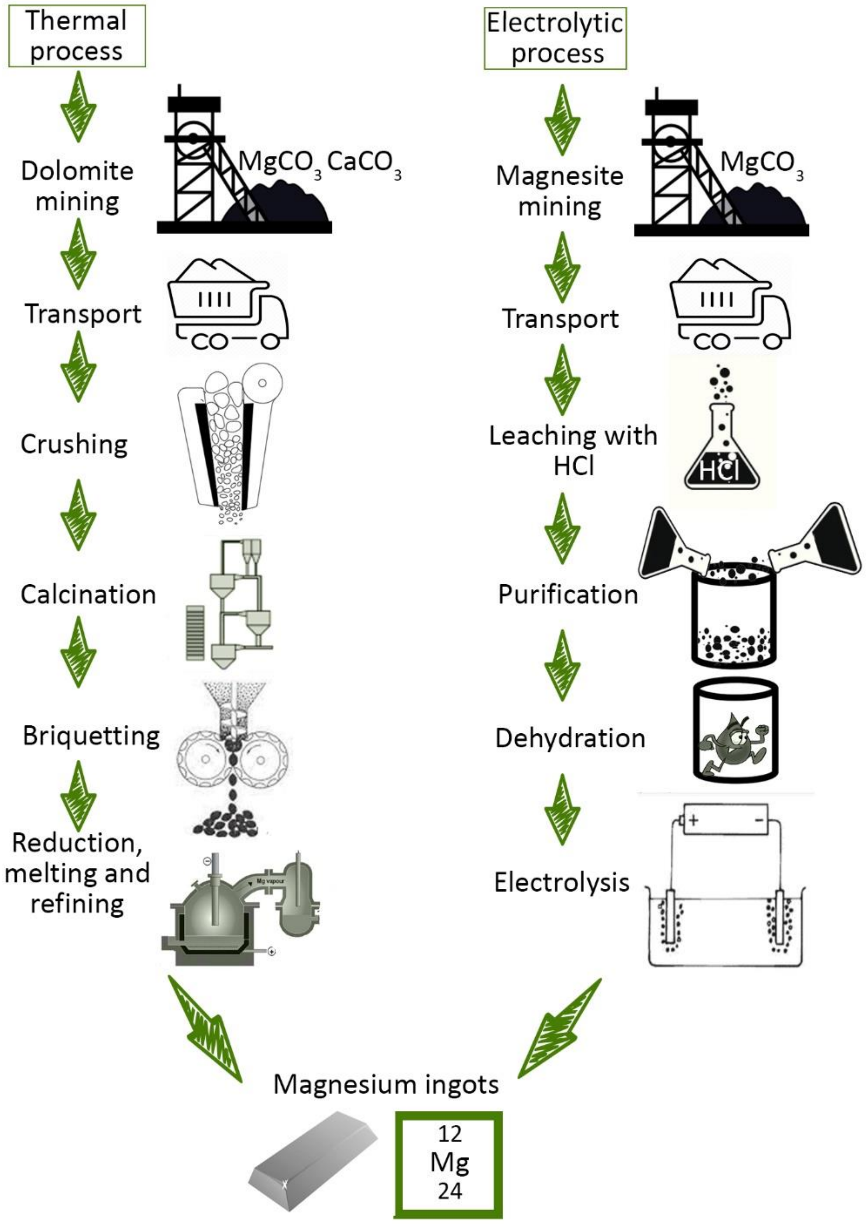

Figure 2. Overview of the primary production of magnesium via thermal reduction and electrolysis.

Table 7. Comparison of electrolytic and thermal reduction processes of Mg (Cherubini *et al.* 2008, Navarro and Zhao 2014, Tian *et al.* 2020).

Process route	**Sources**	**Feed preparation**	**Reaction**	**Temperature/ Pressure**
Electrolysis				
Dow process	Brine/ Seawater	Neutralization, Purification, Dehydration	Overall process: $MgCl_2\rightarrow Mg_{(l)}+1/2Cl_{2(g)}$ Cathode: $2Cl^-\rightarrow Cl_{2(g)}+2e^-$ Anode: $Mg^{2+}+2e^-\rightarrow Mg_{(l)}$	T=700-800 °C P=1 atm
AM process	Magnesite	Mining, Leaching with HCl, Dehydration		
IG Farben process	Seawater/ Brine	Neutralization, Prilling, Dehydration, Chlorination		
Advantage			**Disadvantage**	
• Can be used in many variations • Smaller energy consumption compared to thermal reduction			• Complex purification pretreatment step to produce anhydrous magnesium chloride feed • Large amounts of toxic emissions • Energy intensive	
Thermal reduction				
Silicothermic	Dolomite, FeSi	Calcination, FeSi making, Pelleting	$MgO+CaO+FeSi= Mg_{(g)}+Ca_2SiO_{4(s)}+Fe_{(s)}$	T=1160 °C $P=1.2\cdot10^{-4}$ atm
Carbothermic	Magnesite, Carbon	Calcination, Pelleting	$MgO+C= Mg_{(g)}+CO_{(g)}$	T=1700 °C P=1 atm
Magnetherm	Dolomite, Bauxite, FeSi	Calcination, FeSi making	$2CaO\cdot MgO+(xFe)Si+nAl_2O_3=$ $2Mg+2CaO\cdot SiO_2\cdot nAl_2O_3+xFe$	T=1550 °C P=0.05 atm
Aluminothermic	Dolomite, Al scrap	Calcination	$4MgO_{(s)}+2Al_{(s)}= 3Mg_{(g)}+MgAl_2O_{4(s)}$	T=1700 °C P=0.85-1atm
Mintek	Dolomite, Bauxite, FeSi, Al Scrap	Calcination	$2CaO\cdot MgO+(xFe)Si+nAl_2O_3=$ $2Mg+2CaO\cdot SiO_2\cdot nAl_2O_3+xFe$ $4MgO_{(s)}+2Al_{(s)}=3Mg_{(g)}+$ $MgAl_2O_{4(s)}$	T=1700 °C P=0.85 atm
Advantage			**Disadvantage**	
• No complex purification pretreatment step • The reducing agent (FeSi) can be cost-effectively produced, using a standard submerged arc furnace process and utilizing much of the plant infrastructure at the magnesium plant • Carbothermic method: efficient, low cost, low energy and resource consumption, eco-friendly			• High cost of the reducing agents such as ferrosilicon and (particularly) aluminum • Vacuum needed that causes lower productivity and results in air ingress leading to a loss of magnesium • Large amounts of toxic emissions • Energy intensive	

There are three main thermal processes (1) the Pidgeon process (Mehrabi *et al.* 2012), which uses an externally heated retort, (2) the Magnetherm process that uses electrical resistance heating via an electrode, and (3) the Bolzano (or Bagley or Brasmag) process in which a bed of briquettes comprising ferrosilicon and dolime fines undergo reaction in a furnace using internal electrical heating. The use of vacuum is common to the above thermal processes and magnesium metal is condensed from the vapor phase with the exception of the Magnetherm process where spent products are tapped from the furnace as a slag.

Electrolysis of fused anhydrous $MgCl_2$ is an alternative magnesium production process. Previously, several other treatment methods were used, such as leaching with HCl, purification and dehydration. There are many variations in the way the electrolytic route is applied, depending upon the raw material used, how the raw material is processed to obtain the feedstock for the electrolytic cell, and the design of the cell. The main advantages and disadvantages of thermal reduction and electrolytic processes are discussed in Table 7 (Cherubini *et al.* 2008). It is worth noting that China uses the thermal reduction method, the so-called Pidgeon process. Other large producers of Mg, such as Russia, Israel, Kazakhstan, or Ukraine use the electrolytic process. The USA and Canada use both thermal reduction and electrolytic processes (Cherubini *et al.* 2008).

Equation 4 is intended to calculate energy consumption in the mining stage, in which $EH(t)$ is the total energy consumption for primary production of magnesium for process 'f' (f =1,2) including electrolysis and thermal reduction from sources of energy 'l' (l =1,2,3,…,8): fossil fuel, natural gas fuel, coal, non-fossil fuel, nuclear, renewables, petroleum, and biomass in year *t*; $EG\ (t)$ is the annual rate of energy consumption for primary production of magnesium for process 'f' from sources of energy 'l' calculated from Equation 5; λ_{fl} is the energy consumption coefficient for primary production of magnesium for process 'f' from sources of energy 'l'.

$$EH(t) = \int_{t0}^{t} \big(EG\ (t) \big) dt + EH(t_0) \tag{4}$$

$$EG\ (t) = \sum_{f=1}^{2} \sum_{l=1}^{8} \lambda_{fl}\ \times\ M(t) \tag{5}$$

In Equation 6, $EJ(t)$ is the total energy consumption for primary magnesium casting and molding from sources of energy 'l' (l =1,2,3,…,8): fossil fuel, natural gas fuel, coal, non-fossil fuel, nuclear, renewables, petroleum, and biomass in year *t*; $EI\ (t)$ is the annual energy consumption rate for primary magnesium casting and molding from sources of energy 'l' calculated from Equation 7; α_l is energy consumption coefficient for primary magnesium casting and molding from sources of energy 'l'.

$$EJ\ (t) = \int_{t0}^{t} \big(EI\ (t) \big) dt + EJ(t_0) \tag{6}$$

$$EI\ (t) = \sum_{l=1}^{8} \alpha_l\ \times\ N(t) \tag{7}$$

Water use in the mining stage can be calculated using Equation 8, where $WV(t)$ is the total water use for primary production of magnesium for process '*f*' (*f* =1,2) including electrolysis and thermal reduction from source 'r' (r =1,2,3,4) including water reservoir evaporation, water cooling, water mining and water process in year *t*; $WU(t)$ is the annual rate of water use for primary production of magnesium for process 'f' from source 'r' calculated by Equation 9; τ_{fr} is the coefficient of water used for primary production of magnesium through the process '*f*' by the source 'r'.

$$WV(t) = \int_{t0}^{t} \big(WU\ (t) \big) dt + WV(t_0) \tag{8}$$

$$WU\ (t) = \sum_{f=1}^{2} \sum_{r=1}^{4} \tau_{fr}\ \times\ EG\ (t) \tag{9}$$

In Equation 10, $WY(t)$ is the total amount of water used for primary magnesium casting and molding from source 'r' (r =1,2,3,4) including water reservoir evaporation, water cooling, water mining and water process in year *t*; $WX(t)$ is the annual rate of water used for primary magnesium casting and molding from source 'r' which is calculated using Equation 11; ρ_r is the coefficient of water used for primary magnesium casting and molding from source 'r'.

$$WY\ (t) = \int_{t0}^{t} \big(\ WX\ (t)\big) dt + WY(t_0) \tag{10}$$

$$WX\ (t) = \sum_{r=1}^{4} \rho_r\ \times\ EI\ (t) \tag{11}$$

Processing and primary production generate large amounts of greenhouse gas emissions, which may offset the potential advantage of using magnesium. Primary magnesium production from ores takes place using hydrometallurgical and pyrometallurgical methods. First step of extraction includes hydrometallurgical treatment followed by either thermal reduction (mainly the Pidgeon process) or molten-salt electrolysis. Both thermal and electrolytic processes produce large amounts of toxic emissions and consume a lot of energy as both alternatives operate at high temperatures, roughly from 1160 °C for the Pidgeon Process and 700–800 °C for electrolytic processes (Table 7) (Navarra *et al.* 2021).

Equation 12 describes the calculation of emissions from the mining and processing stage. $GF(t)$ is the total stock of emissions for primary production of magnesium for process '*f*' (*f* =1,2) including electrolysis and thermal reduction for emissions 's' (s =1,2,3,…,12) including HFC-134a, carbon dioxide (CO_2), methane (CH_4), sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), particulate matter of a diameter smaller than 2.5 micrometer (PM2.5), nitrous oxide (N_2O), particulate organic carbon (POC), black carbon (BC), and airborne particulate matter smaller than 10 micrometer (PM10) in year *t*; $GE(t)$ is the annual rate of emission for primary production of magnesium using process '*f*' for emissions 's' calculated by Equation 13.$; and\ \varsigma_{fs}$ is the emission coefficient for primary production of magnesium using process '*f*' for emissions 's'.

$$GF(t) = \int_{t0}^{t} \big(\ GE\ (t)\big) dt + GF(t_0) \tag{12}$$

$$GE(t) = \sum_{f=1}^{2} \sum_{s=1}^{12} \varsigma_{fs}\ \times\ EG\ (t) \tag{13}$$

In Equation 14, $GL(t)$ is the total emission from primary magnesium casting and molding for emissions 's' in year *t*; $GH(t)$ is the annual rate of emission for primary magnesium casting and molding for emissions 's' which is calculated from Equation 15; and χ_s is the emission coefficient for primary magnesium casting and molding for emissions 's'.

$$GL(t) = \int_{t0}^{t} \left(GH(t) \right) dt + GL(t_0) \tag{14}$$

$$GH(t) = \sum_{s=1}^{12} \chi_s \times EI\ (t) \tag{15}$$

2.2 Production stage

In the production stage, the model considers both semi-finished and final products. Equation 16 presents the cumulative amount of Mg used in manufactured semi-finished products in year *t*, $B(t)$; $O(t)$, calculated by Equation 17, is the global annual amount of Mg used in semi-finished products 'k' (*k=1,2,…,6*) including die castings, nodular cast iron, manufacturing of iron and steel, titanium refining, aluminum alloys and other industries; and δ_k is the coefficient of global magnesium used in industry 'k'.

$$B(t) = \int_{t0}^{t} \left(O(t) - N(t) \right) dt + B(t_0) \tag{16}$$

$$O(t) = \sum_{k=1}^{6} B(t) \times \delta_k \tag{17}$$

In Equation 18, $C(t)$ is the cumulative amount of Mg used in manufactured finished products in year *t*; t_0 is the initial time. $P(t)$, which is calculated by Equation 19, is the global annual amount of Mg used in finished products 'm' (*l=1,2,…,5*) including vehicle, aircraft, packaging, construction, and desulfurization agent industry and v_m is the coefficient of global magnesium used in industry 'm'.

$$C(t) = \int_{t0}^{t} \left(P(t) - O(t) \right) dt + C(t_0) \tag{18}$$

$$P(t) = \sum_{m=1}^{5} C(t) \times v_m \tag{19}$$

2.3 Recycling stage

This stage includes collecting end-of-life products containing Mg, recycling of wastes using functional and non-functional processes, and casting and molding of secondary magnesium. Equation 20 represents the cumulative amount of Mg available in the collected end-of-life products in year *t*, $D(t)$. $L(t)$, calculated by Equation 21, stands for the global annual amount of Mg available in the collected end-of-life products 'n' (*n=1,2,…,5*) including vehicles, aircrafts, packaging, construction materials, and iron & steel and φ_n is the coefficient of global collected magnesium from industry 'n'.

$$D(t) = \int_{t0}^{t} \big(L(t) - \ P(t)\big)dt + D(t_0) \tag{20}$$

$$L(t) = \sum_{n=1}^{5} D(t) \ \times \varphi_n \tag{21}$$

Equation 22 represents the cumulative amount of functionally recycled Mg in year *t*, $E(t)$. $Q_g(t)$ calculated by Equation 23 is the global annual amount of functionally recycled Mg from sector 'g' (*g=1,2*) including transportation, and iron & steel and ϱ_g is the coefficient of global functional recycling of magnesium from sector 'g'.

$$E(t) = \int_{t0}^{t} \big(\ Q(t) - \ L(t)\big)dt + E(t_0) \tag{22}$$

$$Q(t) = \sum_{g=1}^{2} E(t) \ \times \varrho_g \tag{23}$$

The cumulative amount of non-functionally recycled Mg in year *t*, $F(t)$ is calculated by Equation 24. In Equation 25, $R_h(t)$ is the global annual amount of non-functionally recycled Mg from sector 'h' (*h=1,2,3*) including transportation, packaging and construction and $\mathcal{E}_h$ is the coefficient of global non-functional recycling of magnesium from sector 'h'.

$$F(t) = \int_{t0}^{t} \big(\ R(t) - \ Q(t)\big)dt + F(t_0) \tag{24}$$

$$R(t) = \sum_{h=1}^{3} F(t) \ \times \mathcal{E}_h \tag{25}$$

Equation 26 shows the total energy consumption for secondary production of magnesium, $EL(t)$, for recycling method 'b' (*b* =1,2) including functional and non-functional recycling from sources of energy 'l' (l =1,2,3,…,8): fossil fuel, natural gas fuel, coal, non-fossil fuel, nuclear, renewables, petroleum, and biomass in year *t*. In Equation 27, $EK\ (t)$ is the annual rate of energy consumption for secondary production of magnesium using recycling method 'b' from sources of energy 'l' and β_{bl} is the coefficient of energy consumption for secondary production of magnesium using recycling method 'b' from sources of energy 'l'.

$$EL(t) = \int_{t0}^{t} \left(EK\ (t) \right) dt + EL(t_0) \tag{26}$$

$$EK\ (t) = \sum_{f=1}^{2} \sum_{l=1}^{8} \beta_{bl}\ \times (Q(t) + R(t)) \tag{27}$$

To calculate the amount of water used in the recycling stage Equation 28 is considered, where $WA(t)$ is the total water use for secondary production of magnesium for recycling method 'b' (b =1,2) [functional or non-functional recycling] from source 'r' (r =1,2,3,4) [water reservoir evaporation, water cooling, water mining and water process] in year *t*. In Equation 29, $WZ(t)$ is the annual rate of water use for secondary production of magnesium using recycling method 'b' from source 'r'. η_{br} is the Coefficient of water use for secondary production of magnesium for recycling method 'b' from source 'r'.

$$WA\ (t) = \int_{t0}^{t} \left(WZ(t) \right) dt + WA(t_0) \tag{28}$$

$$WZ\ (t) = \sum_{b=1}^{2} \sum_{r=1}^{4} \eta_{br}\ \times EK\ (t) \tag{29}$$

Equation 30 represents the total amount of water used for secondary production of magnesium, $GN(t)$ using recycling method 'b' (b =1,2) [functional and non-functional recycling] by the type of emissions 's' (s =1,2,3,…,12) [HFC-134a, CO_2, CH_4, SO_x, NO_x, CO, VOC, PM2.5, N_2O, POC, BC, and PM10] in year *t*. In Equation 31, $GM(t)$ is the annual rate of emissions for secondary production of magnesium using recycling method 'b' by the type of emissions 's' and ξ_{bs} is the coefficient of emission for secondary production of magnesium using recycling method 'b' by the type of emissions 's'.

$$GN(t) = \int_{t0}^{t} \left(GM(t) \right) dt + GN(t_0) \tag{30}$$

$$GM(t) = \sum_{b=1}^{2} \sum_{s=1}^{12} \xi_{bs} \times EK\ (t) \tag{31}$$

Equation 32 corresponds to the cumulative amount of casting & molding of functionally recycled Mg in year *t*, $G(t)$. In Equation 33, $CQ(t)$ is the global annual amount of casting & molding of functionally recycled Mg from sector 'g' (*g=1,2*) including transportation, and iron & steel and y_g is the coefficient of casting & molding of magnesium using global functional recycling from sector 'g' (*g=1,2*) including transportation, and iron & steel.

$$G(t) = \int_{t0}^{t} \left(CQ - L(t) \right) dt + G(t_0) \tag{32}$$

$$CQ(t) = \sum_{g=1}^{2} G(t) \times y_g \tag{33}$$

The cumulative amount of casting & molding of non-functionally recycled Mg in year *t*, $H(t)$ is calculated by Equation 34. In Equation 35, $CR(t)$ represents global annual amount of casting & molding of non-functionally recycled Mg from sector 'h' (*h=1,2,3*) including transportation, packaging and construction and z_h is the coefficient of casting & molding of magnesium using global non-functional recycling from sector 'h'.

$$H(t) = \int_{t0}^{t} \left(CR - Q(t) \right) dt + H(t_0) \tag{34}$$

$$CR(t) = \sum_{g=1}^{2} G(t) \times z_h \tag{35}$$

Equation 36 represents total energy consumption for secondary magnesium casting and molding, $ET(t)$, using recycling method 'b' (*b* =1,2) [functional or non-functional recycling] from sources of energy 'l' (*l* =1,2,3,…,8) [fossil fuel, natural gas fuel, coal, non-fossil fuel, nuclear, renewables, petroleum, and biomass] in year *t*. In Equation 37, $ES\ (t)$ is the annual rate of energy consumption for magnesium casting and molding for recycling method 'b' from sources of energy 'l' and ω_{bl} is the coefficient of energy consumption for secondary production of magnesium using recycling method 'b' from sources of energy 'l'.

$$ET(t) = \int_{t0}^{t} \left(ES\ (t) \right) dt + ET(t_0) \tag{36}$$

$$ES\ (t) = \sum_{f=1}^{2} \sum_{l=1}^{8} \omega_{bl}\ \times (CQ(t) + CR(t)) \tag{37}$$

Equation 38 is formulated to calculate the total water used for secondary magnesium casting and molding, $WD(t)$, in recycling method 'b' (b =1,2) [functional and non-functional recycling] from sources 'r' (r =1,2,3,4) [water reservoir evaporation, water cooling, water mining and water process] in year *t*. In Equation 39 $WB(t)$ is the annual rate of water use for secondary magnesium casting and molding in recycling method 'b' from sources 'r' and Ψ_{br} is the coefficient of water use for secondary magnesium casting and molding in recycling method 'b' from source 'r'.

$$WD(t) = \int_{t0}^{t} \big(GE\ (t) \big) dt + WD(t_0) \tag{38}$$

$$WB\ (t) = \sum_{b=1}^{2} \sum_{r=1}^{4} \Psi_{br}\ \times ES\ (t) \tag{39}$$

Equation 40 represents total emissions for secondary magnesium casting and molding, GP, for recycling methods 'b' (b =1,2) [functional and non-functional recycling] and type of emissions 's' (s =1,2,3,…,12) [HFC-134a, CO_2, CH_4, SO_x, NO_x, CO, VOC, PM2.5, N_2O, POC, BC, and PM10] in year *t*. In Equation 41, $GO(t)$ is the annual rate of emissions from secondary magnesium casting and molding using recycling method 'b' by type of emissions 's', and Θ_{bs} is the coefficient of emission for secondary magnesium casting and molding using the recycling method 'b' by type of emissions 's'.

$$GP(t) = \int_{t0}^{t} \big(GO\ (t) \big) dt + GP(t_0) \tag{40}$$

$$GO(t) = \sum_{b=1}^{2} \sum_{s=1}^{12} \Theta_{bs}\ \times ES\ (t) \tag{41}$$

3. Results and discussion

Chinese producers have dominated the world primary magnesium market for the last twenty years, as it is shown in Figure 3. Magnesium from China accounted for about 45%, 88%, and 86% of the total primary production in 2000, 2010, and 2020, respectively. The estimated results show that by 2050 primary magnesium production in China will increase to 1.5 million tonnes (mt) if current policies are continued and to 1.2 mt if new policies are adopted. It is estimated that other producers of magnesium such as Israel, Brazil, Russia, and Kazakhstan will increase production to 33.6 kt, 35.2 kt, 107.2 kt, 40 kt by 2050, respectively. To diversify the production of magnesium and overcome the monopoly of China new plants have been built in Malaysia, South Korea and Iran, and pilot plants for future operations have been constructed in Australia and Canada. Their potential capacity output has not been considered in this study and could have an impact on future Mg production.

The dashed line in Figure 3 shows a possible decline in China's primary production of magnesium caused by new regulations on energy consumption reduction targets by 2021 as discussed in the Introduction. From the circular economy viewpoint, a considerable part of the gap caused by new regulations in China can be filled by boosting the circularity of magnesium and the efficiency of its recycling. Figure 3 b presents trends in secondary magnesium production in different sectors based on two recycling processes, i.e. functional (F) and non-functional (NF) one. The results show that the largest share of secondary magnesium comes from the transportation sector and could reach around 0.39 mt and 0.59 mt by 2050 obtained through functional and non-functional recycling. It is worth mentioning that technically, it would be possible to separate magnesium from the end-of-life products, but alloys have relatively low volumes per unit which reduces the economic benefits of magnesium recovery.

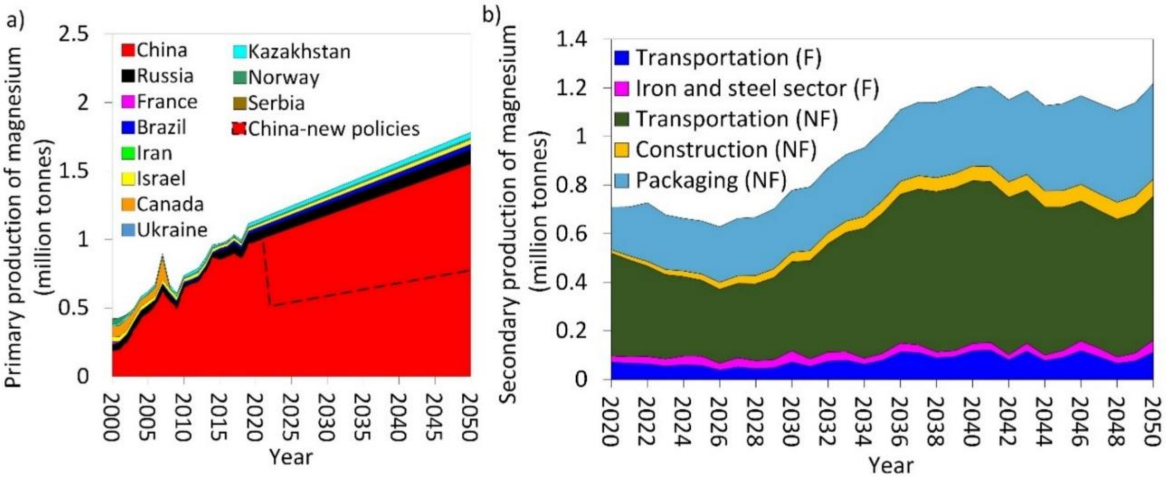

Figure 3. Global primary and secondary magnesium production. a) Mass flows of primary production by countries from 2000 to 2050. b) estimated secondary production of Mg by sector and by recycling processes (F: Functional, NF: Non-functional) from 2020 to 2050.

The production of magnesium is a highly energy-intensive process. Figure 4 depicts global energy consumption of primary production of magnesium in the mining stage by country between 2000 and 2050. The Chinese magnesium mining industry has been making efforts towards decreasing energy consumption and has successfully halved it over last 20 years, particularly, per tonne of magnesium production where a decrease is observed from 11-12 tonnes of coal equivalent (tce) in 2000 to 8–9.5 tce, 4.8–5.2 tce, 4.3–4.7 tce, 4 tce in 2005, 2010, 2015, 2018, respectively. Such a decrease in energy consumption has been made possible by improving technology and putting in place equipment, such as, e.g., a new energy-saving rotary kiln, regenerative reduction furnace, vertical reduction furnace, preheater and a novel regenerative combustion technology offering high energy efficiency (Tian *et al.* 2020). Despite significant technological improvements in primary production, a large scale of magnesium production leads to a remarkable growth of energy consumption in China. Given the increasing Mg production in China by a compound annual growth rate (CAGR) of 6%, the total energy consumption of primary production increased from 96.27 million GJ in 2000 to 331.36 million GJ 2010 and 500.98 million GJ in 2020. It is estimated that the total energy consumption of primary production will increase by about 786.35 million GJ in 2050 if magnesium production continues to grow steadily. Russia, the second top producer of metallic magnesium from primary sources, will increase energy consumption from 33.57 million GJ in 2020 to 51.77 million GJ in 2050. Brazil, Israel and Kazakhstan reported approximately the same levels of energy consumption ~10 million GJ in 2020 and we predict it will double by 2050.

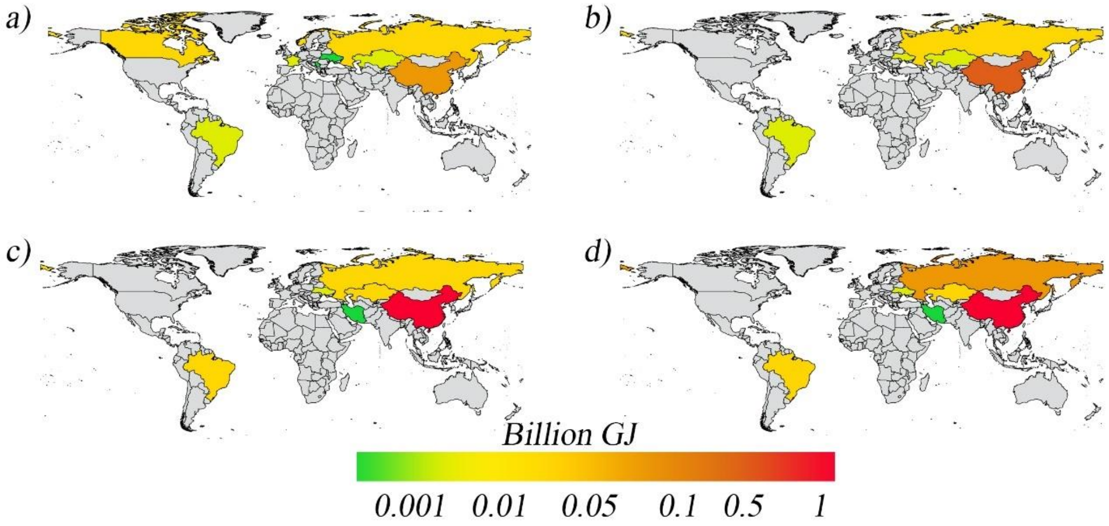

Figure 4. Global energy consumption of primary production of magnesium in mining stage in a) 2000 b) 2010 c) 2020, and d) 2050.

Sustainable water management within the mining industry has become critical as its absence could lead to a severe global water stress in relevant areas. The results highlight issues raised in the Carbon Disclosure Project (CDP) (CDP 2013) on the criticality of sustainable water management, based on the opinion of 64% of mining industries. According to the World Resources Institute (WRI) Aqueduct 3.0 dataset (Luo *et al.* 2015), water stress in areas where magnesium reserves are located, such as Iran, Israel, Kazakhstan, Ukraine is extremely high (>80%). Similar problems are observed in China experiencing medium-high water stress (20-40%); Canada and Russia with low-medium water stress (10-20%), and Brazil, Serbia, and Norway which are in the range of low water stress (<10%). Global water use of primary magnesium production by countries from 2000 and prediction until 2050 are shown in Figure 5.

Primary production of magnesium uses a considerable amount of water in different processes such as mineral processing, dust suppression, slurry transport and employees' needs. In most mining operations, water comes from groundwater sources, streams, rivers, lakes, or commercial water service suppliers. Most industrial fresh water in Mg production is used for cooling the equipment and can be recycled or used for other purposes after purification. China water use for Mg production in 2020 was 0.032 Km^3, followed by Russia 0.003 Km^3, and almost equal water use for Kazakhstan, Israel and Brazil that was approximately 0.001 Km^3. Global estimated water use for Mg production by 2050 will reach around 0.06 Km^3, consumed mainly by China (0.05 Km^3 by 2050) if new policies will fail to change the global distribution of production.

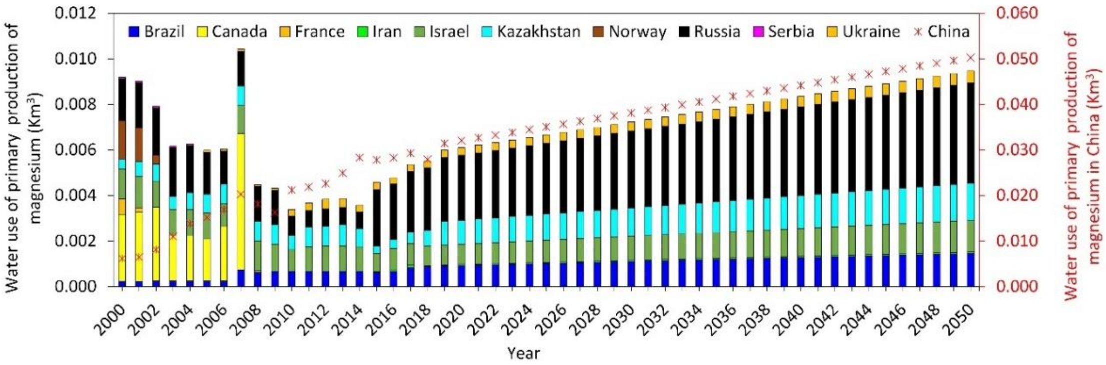

Figure 5. Global water consumption of primary production of magnesium by countries, in millions of cubic meters.

Figure 6. shows the amount of global energy consumption and water use across different processes of primary and secondary production of magnesium presented as M1 – primary magnesium production using the electrolysis method, M2 – primary magnesium production using the thermal reduction method, M3 – primary magnesium casting and molding, M4 – secondary magnesium production, M5 – secondary magnesium casting and molding. As shown

in Figures 6 a and 6 b, the primary production of magnesium by electrolysis, thermal reduction and primary magnesium casting and molding are the most energy intensive and water consuming processes. Particularly, in 2010 energy use for M1, M2 and M3 production flows amounted to 3.1, 2.6, and 3.0 billion GJ and it is estimated that they will increase to 30.5, 25.0 and 30.4 billion GJ by 2050, respectively.

We can see a significant potential contribution of secondary production of magnesium to energy savings (up to 31 billion GJ) and water use (2.7 Km^3) compared to the primary one in 2000-2050. However, detailed calculations show that the improvement of circularity rates of magnesium based on current strategies would be less than 1% from 2020 to 2050, therefore we need to improve policies on the circularity of Mg. Also, the estimates show that global energy consumption of magnesium recycling (5.7 million GJ) and casting & molding (22.5 million GJ) in 2020 will increase to 9.9 million GJ and 38.7 million GJ in 2050, respectively.

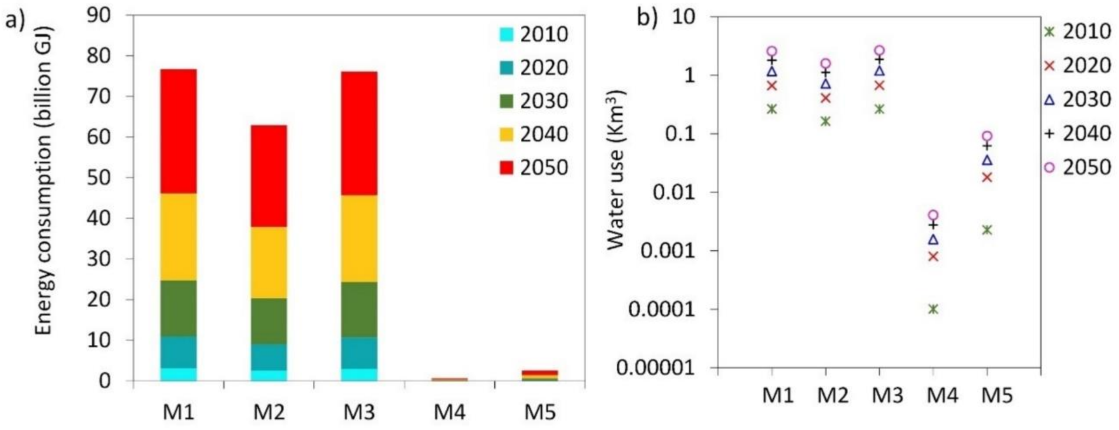

Figure 6. Global energy consumption and water use of M1 – primary magnesium production using electrolysis, M2 – primary magnesium production using thermal production, M3 – primary magnesium casting and molding, M4 – secondary magnesium production, M5 – secondary magnesium casting and molding. a) energy consumption in billion GJ in 10-year interval between 2010 and 2050 and b) water use in Km3 in 10-year interval between 2010 and 2050.

Figure 7 represents the cumulative global emissions from primary and secondary production of magnesium in the period 2010-2050. The production of magnesium using the thermal reduction method releases amounts of SOx that are 5.7 times higher than those from the electrolysis method. Estimates show that the production of magnesium using thermal reduction and electrolysis methods may generate 4.5 and 0.8 mt of SO_x, respectively, by 2050. Besides the SO_x, the highest emissions are observed for CH_4 and NO_x that for the electrolysis method will reach around 1.8 mt of CH_4 and 0.9 mt of NO_x by 2050, and for the thermal reduction method will be around 1.5 and 1.4 by 2050. The results show that the amount of emissions generated by the recycling stage is significantly smaller than for the primary production of magnesium. However, the highest amount of emissions in the recycling stage corresponds to non-functional recycling. As shown by the results, the amounts of CH_4, CO, NO_x, and SF_6 generated by non-functional recycling will reach around 4.5, 1.6, 2.3, and 2.4 kt in 2050, respectively.

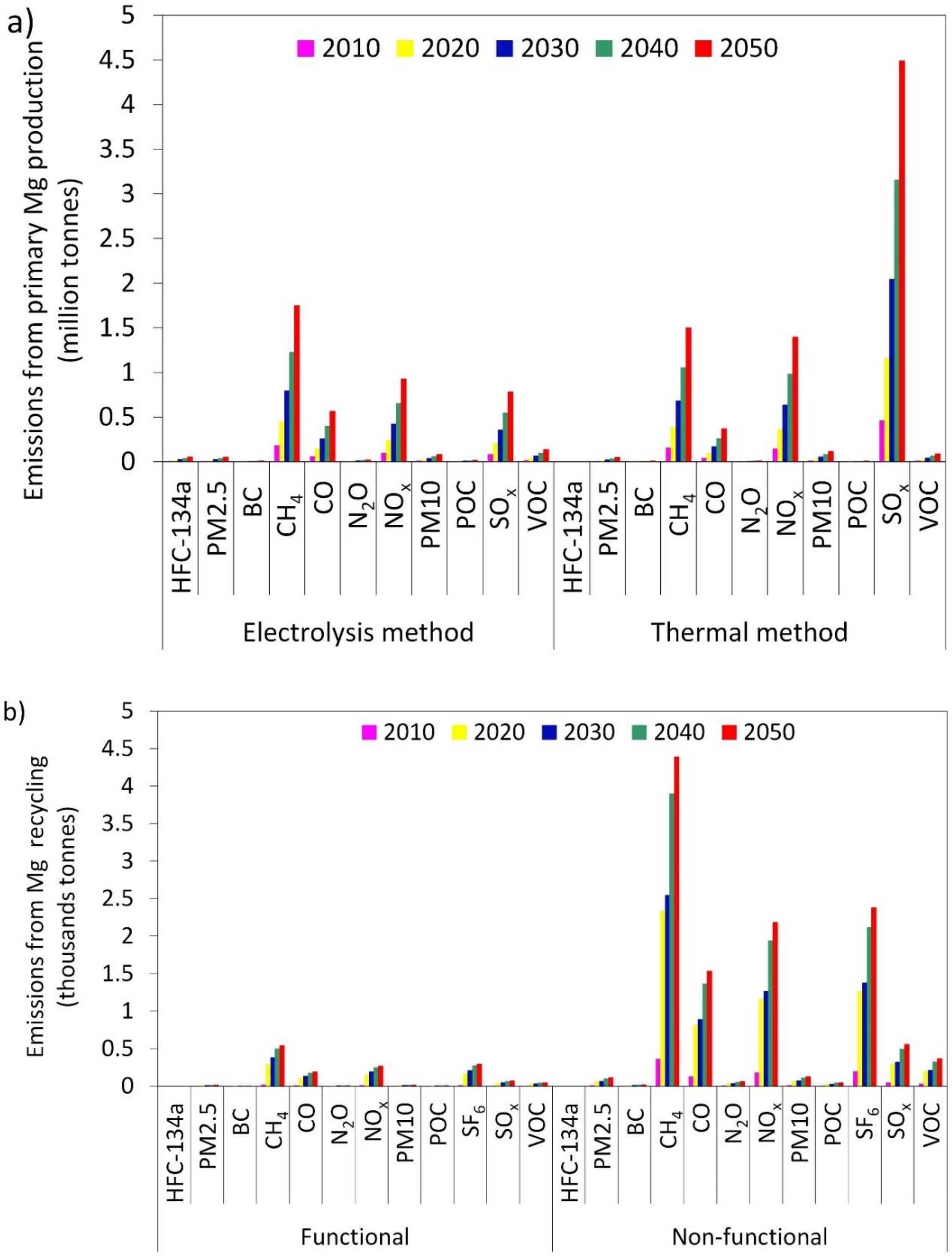

Figure 7. Cumulative global emissions from primary and secondary production of magnesium between 2010 and 2050. a) primary production based on electrolysis and thermal methods b) secondary production based on functional and non-functional recycling.

Cumulative global emissions of Mg casting and molding from primary and secondary production of magnesium are presented in Figure 8. We can observe rather considerable emissions in the casting and molding stage mainly in the primary production. The highest emissions from casting and molding correspond to CH_4 followed by NO_x , SO_x ,CO and VOC in both primary and secondary production. However, there is a significant amount of SF_6 generated in casting and molding of Mg in secondary production. This finding helps us to better understand the essential need to improve technologies and focus on mitigating emissions.

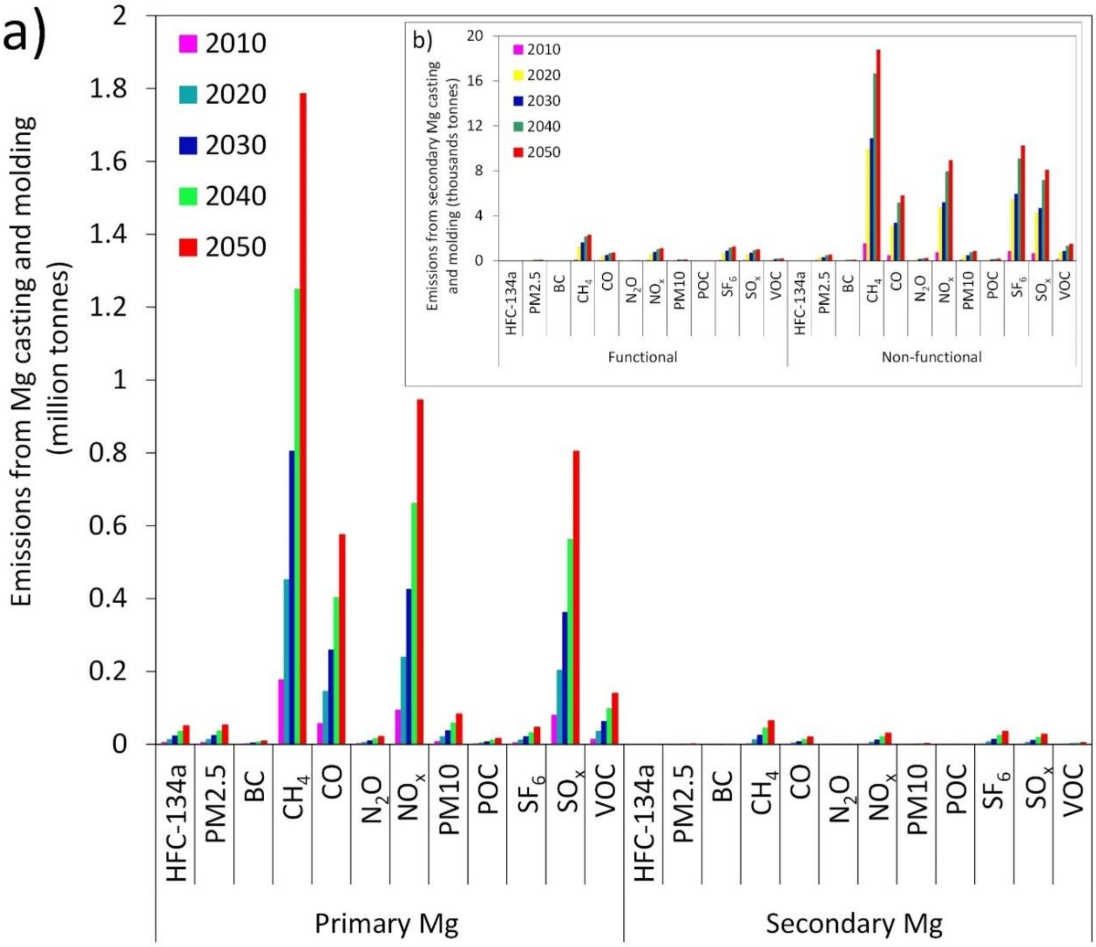

Figure 8. Cumulative global emissions from Mg casting and molding from primary and secondary production (10-year interval) between 2010 and 2050.

Figure 9 shows global greenhouse gas (GHG) emissions from different processes of primary and secondary production of magnesium presented as M1 – primary magnesium production using the electrolysis method, M2 – primary magnesium production using the thermal reduction method, M3 – primary magnesium casting and molding, M4 – secondary magnesium production, M5 – secondary magnesium casting and molding. GHG intensities are calculated using IPCC AR5 100-year Global Warming Potential values (Stocker *et al.* 2013) of 1 (CO_2), 36 (CH_4), and 298 (N_2O). The results show that the highest generation of GHG emissions corresponds to primary magnesium casting and molding, reaching around 3.7 billion tonnes CO_2 eq. The detailed analysis reveals that the circularity of magnesium can eliminate around 3 billion tonnes CO_2 eq, including 0.7 billion tonnes CO_2 eq from secondary production and around 2.3 billion tonnes CO_2 eq from casting and molding of magnesium.

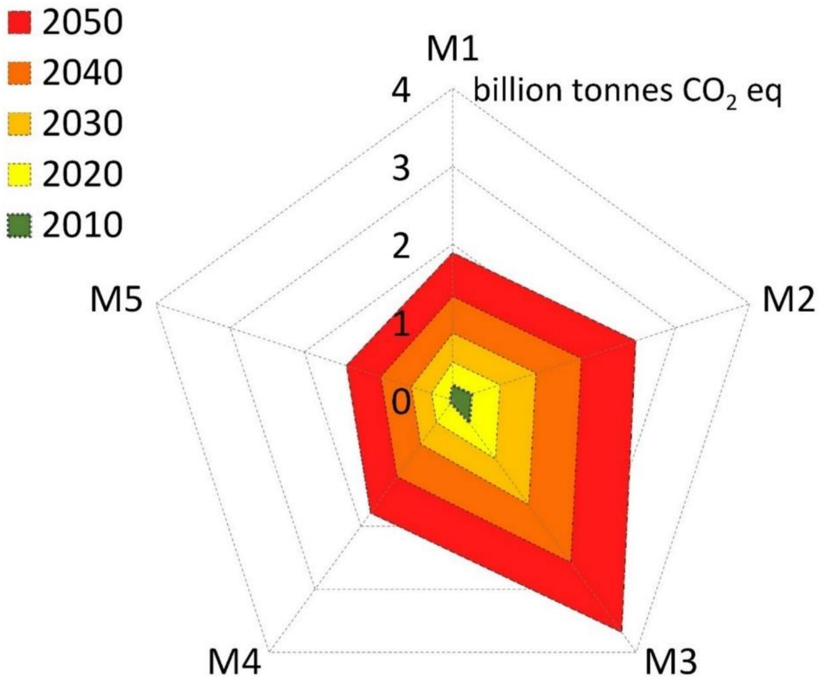

Figure 9. Annual global GHG emissions in billion tonnes CO_2 eq.

4. Conclusions

Sustainable circular economy of magnesium is of major importance due to the relevance of this metal for the manufacturing sector and the competing demand from many regions across the world. Our proposed dynamic model enhances the understanding of a comprehensive environmental impact of circularity of magnesium and supports policy makers in developing appropriate strategies towards achieving sustainability. The obtained results confirm that there are issues involved in circular use of magnesium as the major secondary production comes from non-functional recycling which exerts the highest environmental impact. The examination of the results suggests that new strategies should be proposed and efficient recycling policies need to be developed to provide technologies required to enhance functional recycling of magnesium in several industries such as transportation, iron and steel, packaging and construction. Moreover, our findings highlight the environmental concerns remaining in primary production of magnesium, mainly in the casting and molding stage. Besides energy and water consumption, we need to pay special attention to prevent generating emissions such as CH_4, NO_x , SO_x ,CO, VOC and SF_6 from the production of magnesium. Along these lines, major new technological changes are required to minimize environmental concerns, i.e. we need to improve not only the technical performance, but also environmental performance. Also, the findings show that the absence of established value-added chains for end-of-life scrap containing magnesium adversely affects functional recycling. Therefore, developing sustainable circular economy of magnesium will call for close cooperation alongside the supply chains between industries, operators, distributors, collection centers, and legislators.

Acknowledgments

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Appendix

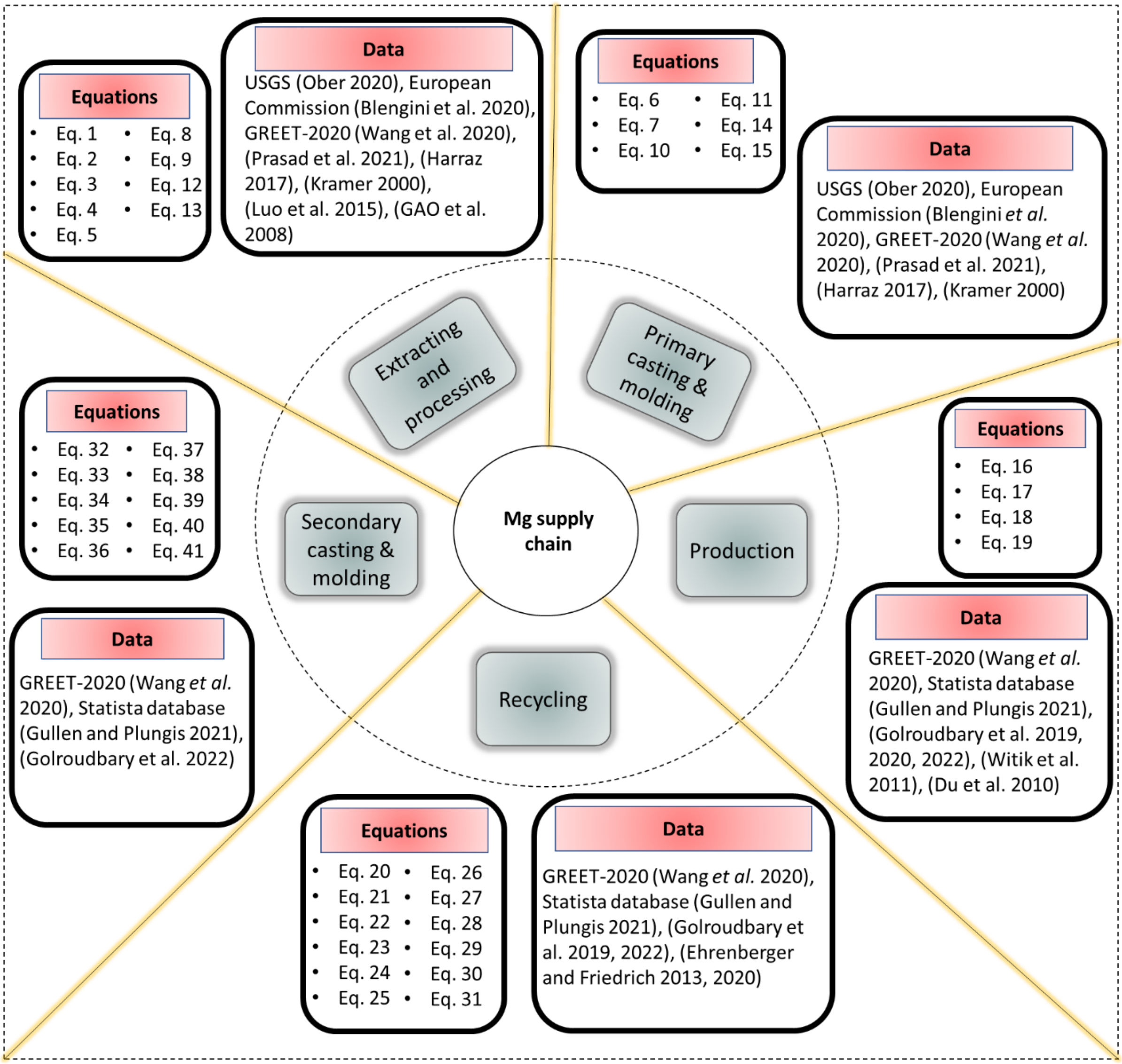

Figure A1. The framework of magnesium model and data sources.

Table A1. Composition of seawater and brine.

Compound	**Michigan**		**Element**	**Persian Gulf, ppm**	
	Seawater, g/L	Brine, g/L		Water(Al Mutaz and Wagialia 1990)	Brine(Al Mutaz and Wagialia 1990)
NaCl	27.319	5.45	Na+K	14800	25650+720

Compound		**Michigan**	**Element**	**Persian Gulf, ppm**	
	Seawater, g/L	Brine, g/L		Water(Al Mutaz and Wagialia 1990)	Brine(Al Mutaz and Wagialia 1990)
$MgCl_2$	4.176	8.2	Ca	14800	80
$MgSO_4$	1.668	-	Mg	1600	2750
$MgBr_2$	0.076	-	HCO_3^-	130	220
$CaSO_4$	1.268	-	SO_4^{2-}	3450	5000
$Ca(HCO_3)_2$	-	-	Cl	25000	35800
K_2SO_4	0.869	-	CO_3^{2-}	40	-
KCl		0.48	F	2	-
			Br-	-	120
			silicon	-	2
Br_2	-	0.2134	TDS*	45000	70000
Specific gravity	1.024	1.264			

*TDS – Total dissolved salt

Table A2. Data for Figure 6. Global energy consumption and water use of M1 – primary magnesium production using electrolysis, M2 – primary magnesium production using thermal production, M3 – primary magnesium casting and molding, M4 – secondary magnesium production, M5 – secondary magnesium casting and molding. a) energy consumption in billion GJ in 10-year interval between 2010 and 2050 and b) water use in Km^3 in 10-year interval between 2010 and 2050.

Production\Year	**2010**	**2020**	**2030**	**2040**	**2050**
Energy consumptions (billion GJ)					
M1	3.14	7.85	13.86	21.39	30.46
M2	2.58	6.44	11.37	17.56	25.00
M3	3.02	7.70	13.71	21.28	30.43
M4	0.01	0.06	0.11	0.20	0.29
M5	0.03	0.22	0.44	0.77	1.14
Water use (Km^3)					
M1	0.2671	0.6682	1.1793	1.8207	2.5923
M2	0.1646	0.4119	0.7269	1.1222	1.5979

M3	0.2656	0.6766	1.2047	1.8708	2.6750
M4	0.0001	0.0008	0.0016	0.0028	0.0041
M5	0.0023	0.0182	0.0358	0.0624	0.0921

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