ANALYSIS OF THE MATERIAL REQUIREMENTS OF GLOBAL ELECTRICAL MOBILITY

Daniel Pulido-Sánchez[1], Iñigo Capellán-Pérez[1], Margarita Mediavilla-Pascual[2], Carlos de-Castro-Carranza[3], Fernando Frechoso-Escudero[4]

[1]Universidad de Valladolid, Escuela de Ingenierías Industriales, Grupo de Energía, Economía y Dinámica de Sistemas (GEEDS), Paseo del Cauce 59, 47011 Valladolid +34 983423545

[2]Universidad de Valladolid, Escuela de Ingenierías Industriales, Departamento de Ingeniería de Sistemas y Automática, Paseo del Cauce 59, 47011 Valladolid +34 983 184539

[3]Universidad de Valladolid, Escuela de Arquitectura, Departamento de Física Aplicada, Av. Salamanca 18, 47014 Valladolid +34 983 423132

[4]Universidad de Valladolid, Escuela de Ingenierías Industriales, Departamento de Ingeniería Eléctrica, Paseo del Cauce 59, 47011 Valladolid +34 983 184544

Received: 03/08/2020 • Reviewing: 02/09/2020 • Acepted: 03/11/2020 • To cite this article: PULIDO-SÁNCHEZ, Daniel; CAPELLÁN-PÉREZ, Iñigo; MEDIAVILLA-PASCUAL, Margarita; DE-CASTRO-CARRANZA, Carlos; FRECHOSO-ESCUDERO, Fernando. ANALYSIS OF THE MATERIAL REQUIREMENTS OF GLOBAL ELECTRICAL MOBILITY. DYNA. March 2021, vol. 96, no. 2, 7 pp. DOI: https://doi.org/10.6036/9893

ABSTRACT:

Today, we are witnesses to the early days of a change in mobility technology as oil reserves decline and society's environmental awareness increases. Electric technologies are intended to replace those based on hydrocarbons as they have been initially conceived as more environmentally friendly and energy efficient. However, the problem of the future availability of the materials required for this change has arisen. A large demand for this type of mobility could contribute to the depletion of these resources, leading to major problems for the manufacture of vehicles and all other technologies that use these materials if we do not find alternatives that allow us not to deplete these natural resources. These alternatives may involve not only a change in the materials used in electric vehicles but also the use of different modes of transport.

The MEDEAS system dynamics simulation model will be used to help us estimate which materials related to the transition in the transport sector might be most critical in the future globally. Once the simulations of different scenarios have been run, we observe that aluminum, copper, cobalt, lithium, manganese and nickel have such a high demand that it would practically exhaust the reserves in several scenarios, so we will propose alternative measures to try to avoid their exhaustion due to the use of this type of mobility.

Keywords: *Transport modes, mineral resources, system dynamics, lithium-ion batteries.*

1.- INTRODUCTION

The global increase in greenhouse gas (GHG) emissions and the depletion of good quality oil reserves are two of the biggest challenges facing humanity at the moment. The transport sector, which symbolizes modern social and economic relations like no other, is centrally affected by these two problems.

Globally and throughout 2014, the transport sector emitted 20% of all GHG emissions [1]. These emissions are unevenly distributed among the different countries, highlighting those with the highest GDP [2]. Within the European Union (EU-28), transport is the only one that increased its GHG emissions, compared to 1990 those of 2017 were 28% higher, resulting in 27% of total EU-28 emissions [3].

This has led to cleaner and more efficient mobility systems than current ones being promoted from various institutions, including electric mobility. However, electrical mobility, a priori more environmentally friendly, has the associated problem that some of the materials present in several of the elements of this technology, such as electric motors and batteries, are critical elements [4], that is, can present problems of exhaustion in the near future [5], [6].

Several authors have pioneered attempts to draw attention to the problem of the depletion of mineral resources needed in the different technologies used to reduce GHG emissions and the use of fossil fuels in modern societies, such as photovoltaic technology or electric vehicles. A.Valero et al [5] estimated the mineral requirements of various technologies, such as electric vehicles, until 2050 using an extrapolation of current trends; Junne et al [7] manages to estimate the demand for minerals considering various types of batteries and technologies through a static analysis using exogenous scenarios; K.Tokimatsu et al [8] uses a model that integrates energy, materials and a simplified climate model to evaluate and estimate the mineral requirements of various technologies in 2 scenarios based on the 2ºC limit in the year 2100; A. García Olivares et al [9] estimates the mineral requirements of various technologies by deepening the elements used in the field of electrified transport, with an extrapolation of current trends that, assume linear demands of minerals. These authors conclude that a large number of materials, such as aluminum, copper or lithium of primary or recycled origin, will be needed, many of them scarce, difficult to obtain and expensive, if the current mobility, based mainly on hydrocarbons, is to be modified towards one based on electricity. Therefore, this study is carried out, seeking to obtain an estimate of the trends adopted by the amount of materials required by this type of mobility in different scenarios with respect to its reserves over time.

This study has increased the accuracy of the work presented above. This has been achieved, firstly, by paying particular attention to the aspect of electric mobility, in the second instance, by implementing a comprehensive bibliographic review in order to obtain the most accurate information on the technologies used in electrified transport and which materials are employ, and finally, using the MEDEAS-World open source dynamic systems model [10], [11], through which realignments between the different economic and energy sectors can be taken into account, since the previous authors simply extrapolated the current trends. MEDEAS-World had only one electric battery technology and this study has extended this aspect to 5 sub-ecologies, and the materials needed for vehicle charging points and the infrastructure needed for the movement of electrified railways have also included.

MEDEAS has been developed with the aim of informing decision-making to achieve the transition to sustainable energy systems, focusing on biophysical, economic, social and technological constraints and addressing some of the limitations identified in the current integrated simulation-assessment models. The MEDEAS model includes the representation of biophysical limitations on energy availability; modelling investments in minerals and energy for the energy transition, enabling a dynamic assessment of potential mineral shortages and the calculation of the net energy available to society; a consistent representation of climate change damage; the integration of a detailed sectoral economic structure (input-output analysis); energy changes driven by physical scarcity; and a rich set of indicators of socio-economic and environmental impact.

2.- MATERIALS AND METHODS

2.1 METHODOLOGY

The MEDEAS-World system dynamics model has been used in order to know the feasibility of continuing to use the aforementioned materials in the future or whether, due to the use of these materials, their global reserves could be wiped out. In order to simulate the model, certain questions must be answered first: what materials does this technology use, in what quantity, what are the reserves of these materials worldwide, and how many of these materials are recycled and by what percentage?

These are the steps that have been taken for the development of this work:

- Assess the current transport situation to understand the magnitude and extent of the problems attached to the electrification process in the near future.
- Estimate, within electrical mobility technologies, what will stand out in the future, what their demand will be, what infrastructures are needed for their implementation, what are the materials used by the technologies and their infrastructures.
- Obtain data on the amount of material reserves present globally of materials used in electric mobility, visualize which materials are currently recycled, in what percentage and how this may vary in the future.
- Integrate all the data into the MEDEAS-W model to simulate the change of mobility worldwide, identifying all the variables to be able to make a complete and as accurate model as possible.
- Obtain the results and interpret them by observing, in the simulation, which materials may be critical (desupply) in the future and what limitations the technology used may have because of this.
- Show possible alternatives or solutions in the use of materials and transport to prevent the desupply of materials in the future and to ensure the use of this technology.

2.2 DATA FOR SIMULATION

First, a large amount of data has been obtained on electrical mobility and all its elements, so as to be able to introduce these as inputs in the MEDEAS-W system dynamics model. To this end, an extensive literature review has been carried out [12]. The first of these data is the number of vehicles being driven on the world´s road [13]. In total, in 2015, an estimated 947,080,000 passenger vehicles and 335,190,000 goods vehicles were calculating worldwide. Neither single-person mobility vehicles nor 2-wheeled vehicles have been counted due to the lack of up-to-date data on such vehicles.

Table 1 presents the models of batteries that have been considered most relevant in electrified transport (taking into account factors such as the materials they consist of, efficiency, market share...) and the weight of each of the elements that make up the batteries per MW of power that has been obtained through the total mass of the batteries per MW, the mass percentages of their elements, the capacity of the batteries and the weight of the cathode elements by battery capacity [14]-[17].

	LiMnO2 battery (kg/MW)	NMC-622 battery (kg/MW)	NMC-811 battery (kg/MW)	NCA battery (kg/MW)	LFP battery (kg/MW)
Aluminum	500	693	693	375	1478
Copper	289	429	429	227	855
Iron	0	0	0	0	765
Lithium	34	71	60	31	96
Manganese	509	110	55	0	0
Nickel	0	335	412	192	0
Cobalt	0	110	55	40	0
Phosphorus	0	0	0	0	425
Other	780	1050	1050	580	2500

Table 1. Weight of each of the elements that make up the batteries selected by MW of power..

In the simulation, these batteries have been independently simulated, as if all electric vehicles used the same type of battery in each simulation. Work is under way to implement a system that allows the simulation with various types of batteries at the same time in the near future, so as to be able to project a better reflection of reality.

The requirements of the batteries are not the only ones that the electrified vehicle have, it also has a large amount of copper in addition to the battery contents [18], shown in Table 2.

	Copper (kg/Vehicle)			
Parts of the vehicle (not counting the battery)	**HEV**	**PHEV**	**BEV**	**Hybrid Bus**
Inverter	0,31	0,3	0,31	1
Electric motor	5	5	9,88	20
High voltage connection	5	5	5	11
Low voltage connection	23	23	23	40
Other	5	5	5	5
Total	38,3	38,3	43,2	77

Table 2: Amount of copper used according to vehicle type, not counting the battery.

In addition to the material requirements of the electrified vehicle, the charging points, the requirements [19] of which have been set out in Table 3, must be taken into account. The shelf life [19] and number [12] of these elements have also been estimated, allowing the demand for minerals over time to be obtained.

Material	Home charger (kg/unit) (3.7 kW)	Conventional charger (kg/unit) (45 kW)	Fast charger (kg/unit) (200 kW)
Copper	0	0	120
Iron	0	0	180
Cement	0	1200	2400
Stainless steel	3,5	2,14	90
Pvc	7,5	0	0
ABS, fiberglass...	0	52,5	380
Lifespan (Years)	15	10	12

Table 3: Weight of each of the elements that make up the load and service life points.

A network connection infrastructure to the charging point is also required to power the latter with electrical power. The demand for minerals from this infrastructure has been set out in Table 4 [12], [20]-[22]. The lifespan of these infrastructures [23] and their length [12] have been estimated in order to obtain the possible temporal evolution of their mineral requirement.

Materials	Low voltage networks (kg/m)	Medium-low voltage networks (kg/m)	Medium-high voltage networks (kg/m)	High voltage networks (kg/m)
Copper	0,044	0	0	0
To	0	0,173	1,215	1,215
Galvanized steel	0	0	0,45	0,45
Steel bar	0	0	2,48	2,48
Cement	0	0	180	180
Pvc	0	0	11	11
Lifespan (years)	40			

Table 4: Weight of each of the elements that make up the electrical power transmission and service life networks.

Electrified rail transport also demands a large amount of minerals [24]. This study has focused on the copper used in infrastructures that allow electrified rail to circulate. Information has been collected [25]-[27] in order to obtain the demand for minerals (copper) that this type of transport would present over time.

Data relating to rail transport	
World railway length (km)	1142014
Percentage of electrified railways (%)	27%
Percentage of double, triple... (%)	50%
Road life (years)	60
Catenary's lifespan (years)	20
Iron copper(kg/km)	10836

Table 5: Amount of copper used according to vehicle type, not counting the battery.

Finally, Table 6 lists the current reserves, resources [28], [29] and recycling situation [6], [30], [31] (stating their recycling ratios) of the main metals used in electrical mobility.

	Lithium	Nickel	Cobalt	Manganese	Aluminum	Copper
Resources (Mt)	40	130	145	1030	7,5 10^4	2100
Reserves (Mt)	14	81	7,2	570	2,8 10^4	720
RC (UNEP) (Melin) (%)	15	35	32	37	35	28,5
Recycling ratios come from UNEP [30]**, except lithium, which come from Melin** [31]**.**						

Table 6: Resources, reserves and recycling rates of various minerals worldwide.

All these data have been entered into the MEDEAS-World database and modelling structures have been modified to dynamically compute the associated mineral requirements. It should also be stated that the mineral requirements that do not belong to the electrified transport sector (rest of the economy) follow economic trends, thus projecting GDP trends from the historical data of each ore.

2.3 SIMULATION: MEDEAS MODEL AND ADOPTED SCENARIOS

Once the above data have been obtained, they can be introduced into the MEDEAS-World model so that, together with various policies or scenarios that we will establish in order to imitate the different physical regulations, policies... the program simulates the behavior of a world, as real as possible, in order to obtain the mineral requirements of electric mobility.

Four scenarios have been simulated, designed and documented in detail, in de Blas et al's article [32], to analyze the main dynamics of global transport material expenditures. The four scenarios focus on the transport sector and the rest of the model follows by extrapolating the observed trends. These scenarios have been taken with the aim of seeing trends in the material requirements of electric mobility over a wide spectrum. The four simulated scenarios are:

1- Expected EV trends: In this scenario, the target percentage of each type of vehicle in 2050 is determined by the observed trends. The targets of light vehicles and buses are set the same as domestic vehicles. Hybrid and gas heavy vehicles have a negligible target percentage, as their growth in this decade has been virtually zero. Train targets maintain current levels.

2- EV High: This is a hypothetical scenario of very high electrification in ground transport. By 2050, all personal cars, buses and motorcycles are supposed to be replaced by battery electric vehicles and 80% of heavy vehicles will be hybrid. This scenario is not intended to be realistic, but serves as an example of extreme electrification without changes in the cultural patterns of transport.

3- E-bike: This scenario promotes mobility based on very light electric vehicles. Most personal cars are supposed to be replaced by two-wheeled electric vehicles, electronic bikes and non-motorized modes. Charging vehicles continue to be based on liquid fuels due to limitations in generalizing large-scale heavy batteries. There is supposed to be a modal shift from heavy trucks to the electric railway where by the proportion of freight transport activity covered by the electric railway increases.

4- Degrowth: This scenario meets the objectives of decarbonization and adaptation to the oil peak through a reduction in total transport demand combined with changes in vehicles. The proportion of vehicles is the same as in the E-bike scenario, but assuming that the demand for transportation from homes is greatly reduced. A modal shift from heavy trucks to electric rail is assumed where by the proportion of freight transport activity covered by the electric railway increases. This scenario points to a stable state economy of $5,000 on average per capita by 2050.

In addition, the three high EV, E-bike, and Degrowth scenarios assume that current recycling rates will be doubled during the simulation period [32].

3.- RESULTS AND DISCUSSION

Following the simulations of the different scenarios, the results set out in Table 7 are obtained, the percentages of the requirements of the different minerals with respect to their reserves in the different fields of electrification technology and in the rest of the economy. It should be remembered that, in the simulation, a single battery used since 2015 has been chosen so that each value of the different batteries in the table is independent, reflecting the requirement of materials in the event that only that battery is used from 2015 onwards.

It has been observed from the simulations that the most critical minerals are aluminum, copper, cobalt, lithium, manganese and nickel. In the case of aluminum, the mineral requirement of the rest of the economy (7%-12%) and the requirement of batteries (0.1%-1.5%). Copper is in high demand from the rest of the economy (87%-123%), but also has notable demand from vehicles (1.5%-8.5%), infrastructure (4%-9.4%) and batteries (4%-42%). Cobalt is in high demand because of the manufacture of batteries (33%-487%), with the exception of the LFP battery, which does not have this mineral. In the case of its demand from the rest of the economy (51%-81%), it can be stated that it is important, but less influential than the demand for batteries. Lithium has very high requirements from all batteries (22%-363%) and reduced demand from the rest of the economy (5%-7%). Manganese presents a significant but contained demand from LMO and NMC batteries (0.5%-24%), though it is in the requirements of this mineral in the rest of economy where it stands out (80%-128%). Finally, nickel is in high demand from NMC and NCA batteries (13%-144%), but its main demand comes from the rest of the economy (82%-130%). All these statements on requirements can be clearly seen in Figure 1.

The batteries that have required the least materials are NCA and LFP (Table 7). The NMC battery has been surpassed in performance and mineral use by the NCA. The LiMnO2 battery has a very poor performance, which is why it has been disused in the electric automotive. In addition, the LFP battery, the only one that does not use critical materials in the cathode (apart from lithium), also has a poor performance, requiring very large batteries (in size and weight) to equalize the capacity and power of batteries that use cobalt.

The cargo infrastructure, rail and copper used in electrified vehicles can add up to more than 17% of the requirement of copper reserves in the most unfavorable scenario (high EV) and 7% in the most favorable (degrowth), so they are elements to be taken into account.

The "Degrowth" scenario tells us that the demand for certain minerals in the field of transport can be reduced. This is the only scenario whose trends in mineral requirements do not rise exponentially. In addition, it is a scenario that reduces greenhouse gas emissions by 80% by 2050 in the field of transport [32].

A reduced uncertainty of some of the hypotheses, measured through a sensitivity analysis, such as the lengths taken at the loading points and their number [12], has been found. This type of analysis has also been assessed, as the demand for some ores could change by varying their recycling ratio; for instance, varying the rate of lithium by 65%, it has been concluded that recycling is of great importance, as there has been a variation in lithium demand of more than 100% of its reserves.

			Expected EV Trends	EV High	E-bike	Degrowth
Aluminum in 2050 for electrification	Infrastructure and chargers		0,08%	0,12%	0,08%	0,04%
	EV batteries	LiMnO2	0,3%	0,5%	0,17%	0,10%
		NMC-622	0,4%	0,68%	0,23%	0,13%
		NMC-811	0,4%	0,68%	0,23%	0,13%
		NCA	0,2%	0,38%	0,12%	0,07%
		LFP	0,89%	1,45%	0,49%	0,28%
Aluminum in 2050 from the rest of the economy			11,8%	9,10%	9,05%	7,45%
Copper in 2050 for electrification	Infrastructure and chargers		3,96%	9,38%	7,49%	3,68%
	Vehicles (without battery)		4,63%	8,5%	2,4%	1,35%
	EV batteries	LiMnO2	7,8%	14,76%	4,92%	2,74%
		NMC-622	11,53%	21,64%	7,21%	4,02%
		NMC-811	11,53%	21,64%	7,21%	4,02%
		NCA	6,19%	11,79%	3,93%	2,19%
		LFP	22,8%	42,47%	14,19%	7,94%
Copper in 2050 from the rest of the economy			123%	103,8%	103,3%	86,53%
Cobalt in 2050 for electrification	EV batteries	LiMnO2	0%	0%	0%	0%
		NMC-622	281,63%	487,71%	162,04%	91,39%
		NMC-811	140,81%	243,91%	80,99%	45,69%
		NCA	102,76%	178,63%	58,99%	33,22%
		LFP	0%	0%	0%	0%
Cobalt in 2050 from the rest of the economy			80,86%	66,59%	67,06%	51,03%
Lithium in 2050 for electrification	EV batteries	LiMnO2	58,88%	132,83%	43,55%	23,78%
		NMC-622	122,08%	274,27%	90,43%	49,43%
		NMC-811	103,33%	232,25%	76,63%	41,82%
		NCA	52,61%	118,72%	38,90%	21,24%
		LFP	162,66%	363,65%	120,77%	66,09%
Lithium in 2050 from the rest of the economy			6,55%	6,35%	6,4%	4,86%
Manganese in 2050 for electrification	EV batteries	LiMnO2	15,62%	23,92%	7,9%	4,46%
		NMC-622	3,5%	5,30%	1,75%	0,97%
		NMC-811	1,87%	2,81%	0,91%	0,48%
		NCA	0%	0%	0%	0%
		LFP	0%	0%	0%	0%
Manganese in 2050 from the rest of the economy			127,62%	96,69%	97,47%	79,79%
Nickel in 2050 for electrification	EV batteries	LiMnO2	0%	0%	0%	0%
		NMC-622	72,87%	117,62%	39,16%	22,33%
		NMC-811	89,67%	144,81%	48,17%	27,45%
		NCA	41,87%	67,80%	22,44%	12,76%
		LFP	0%	0%	0%	0%
Nickel in 2050 from the rest of the economy			129,73%	101,37%	101,63%	81,99%

Table 7: Material requirements for percentage reserves in all 4 scenarios

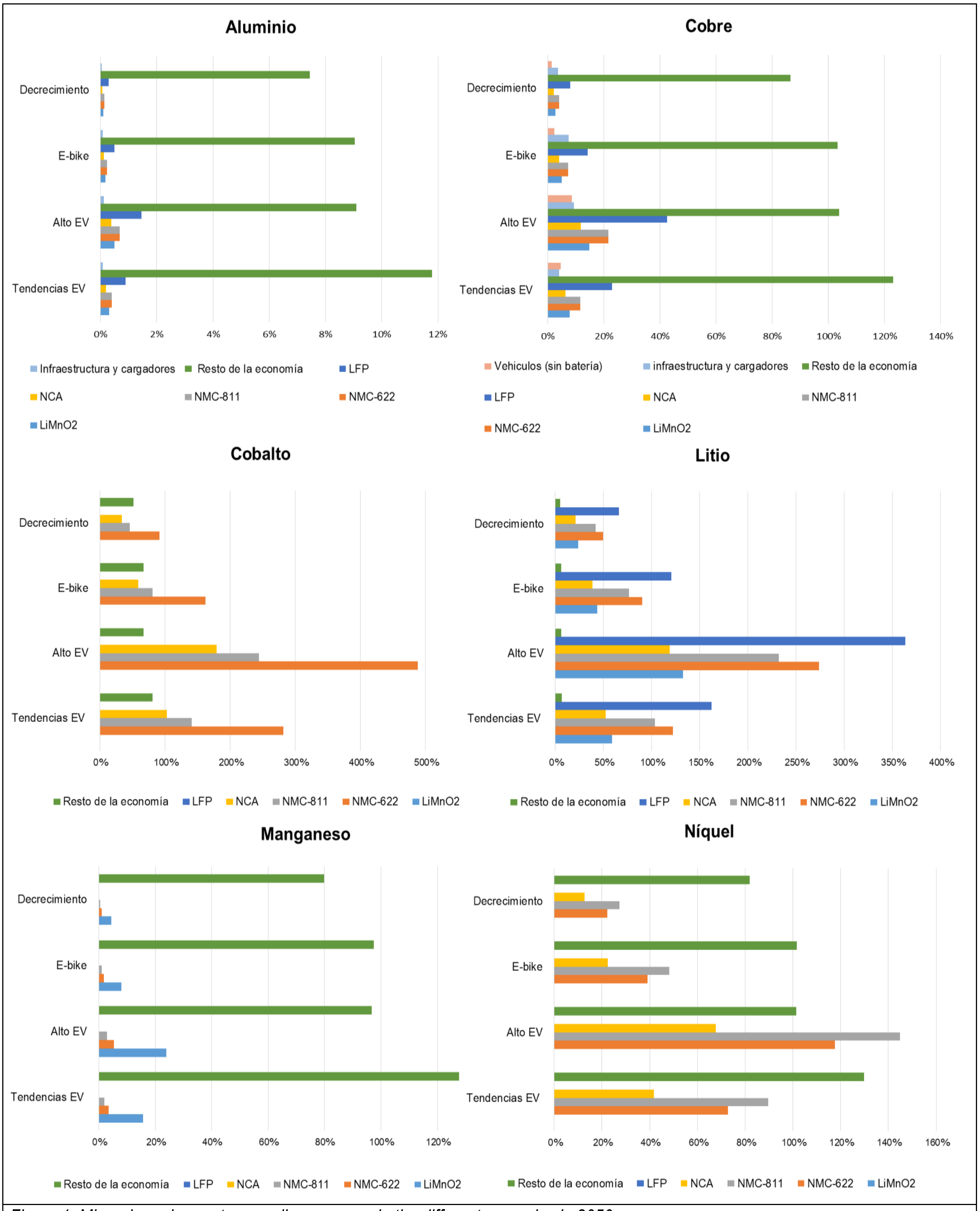

Figure 1: Mineral requirements regarding reserves in the different scenarios in 2050

4.- CONCLUSIONS

The objective of this work has been to study the shift towards electrified mobility in terms of the use of the planet's mineral resources and to analyze its feasibility in a context of the use of this technology in order to reduce GHG emissions [32]. A great deal of information has been obtained on the technologies used in transport electrification. The subsequent introduction of the said data into the MEDEAS-World model has allowed us to explore what might be the possible future of the minerals used in electrification and how they influence the imposition of different scenarios or policies [12].

The results show that alternatives should be sought, as electric mobility technology uses a large amount of minerals at the present time, as has been obtained in the results of the simulations. The alternatives that can be taken, seeking to reduce the effects of this mobility on the resources, lie in adopting socio-economic customs such as those assumed in Scenario 4, Decline, a large reduction in the demand for transport by households, a large reduction in the use of air and sea transport, taking on a massive use of rail for freight transport rather than long-distance road transport, and finally a stable state economy. The application of these alternatives in the model, together with solutions such as the circular economy or mass recycling, shows that it is possible to control the expenditure of certain minerals in the field of transport and also reduce emissions. All these measures can allow our lives to be developed using electric mobility in a sustainable society.

From these alternatives, it has finally been possible to conclude that a change of mobility without changing our habits and customs would not serve to reduce our problems with the environment and with our planet, but rather to aggravate them, because what would we do if these resources were exhausted? What would happen to all the technological elements that use them? Would we have to resume the manufacture of combustion vehicles, one of the large emitters of GHGs [33] and therefore important participants in the problem of climate change?

This article ends by stating some of the limitations present in this study, such as the impossibility of simulating different types of batteries at the same time; no data have been entered on the modification of urban planning; and, in addition, there is great uncertainty in the estimates of reserves and mineral resources.

REFERENCES

[1] Banco Mundial, «Emisiones de CO2 originadas por el transporte (% del total de la quema de combustible)», *Banco Mundial*. https://datos.bancomundial.org/indicator/EN.CO2.TRAN.ZS.

[2] Intergovernmental Panel on Climate Change y O. Edenhofer, Eds., *Climate change 2014: mitigation of climate change: Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press, 2014.

[3] European Environment Agency, «Greenhouse gas emissions from transport in Europe», *European Environment Agency*. https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12.

[4] European Comission, «Critical raw materials». https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en.

[5] A. Valero, A. Valero, G. Calvo, y A. Ortego, «Material bottlenecks in the future development of green technologies», *Renew. Sustain. Energy Rev.*, vol. 93, pp. 178-200, oct. 2018, doi: https://doi.org/10.1016/j.rser.2018.05.041.

[6] H. U. Sverdrup, K. V. Ragnarsdottir, y D. Koca, «An assessment of metal supply sustainability as an input to policy: security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity», *J. Clean. Prod.*, vol. 140, pp. 359-372, ene. 2017, doi: https://doi.org/10.1016/j.jclepro.2015.06.085.

[7] T. Junne, N. Wulff, C. Breyer, y T. Naegler, «Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt», *Energy*, vol. 211, p. 118532, nov. 2020, doi: https://doi.org/10.1016/j.energy.2020.118532.

[8] K. Tokimatsu *et al.*, «Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2 °C target», *Appl. Energy*, vol. 207, pp. 494-509, dic. 2017, doi: https://doi.org/10.1016/j.apenergy.2017.05.151.

[9] A. García-Olivares, J. Ballabrera-Poy, E. García-Ladona, y A. Turiel, «A global renewable mix with proven technologies and common materials», *Energy Policy*, vol. 41, pp. 561-574, feb. 2012, doi: https://doi.org/10.1016/j.enpol.2011.11.018.

[10] I. Capellán-Pérez *et al.*, «MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints», *Energy Environ. Sci.*, vol. 13, n.º 3, pp. 986-1017, 2020, doi: https://doi.org/10.1039/C9EE02627D.

[11] J. Solé *et al.*, «Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model», *Renew. Sustain. Energy Rev.*, vol. 132, p. 110105, oct. 2020, doi: https://doi.org/10.1016/j.rser.2020.110105.

[12] D. Pulido Sánchez, «Análisis de los requerimientos materiales de la transición hacia una movilidad eléctrica», info:eu-repo/semantics/bachelorThesis, 2020.

[13] OICA, «Vehículos en uso», *OICA*. http://www.oica.net/category/vehicles-in-use/.

[14] J. B. Dunn, L. Gaines, M. Barnes, J. L. Sullivan, y M. Wang, «Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle», ANL/ESD/12--3 Rev., 1177517, ene. 2014. doi: https://doi.org/10.2172/1177517.

[15] A. E. Rodríguez, «PROTAGONISMO DE LAS MATERIAS PRIMAS MINERALES EN EL DESARROLLO DEL VEHÍCULO ELÉCTRICO», p. 14.

[16] L. Gaines y P. Nelson, «Lithium-Ion Batteries: Possible Materials Issues», p. 17.

[17] J. B. Dunn, L. Gaines, J. C. Kelly, C. James, y K. G. Gallagher, «The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction», *Energy Environ. Sci.*, vol. 8, n.º 1, pp. 158-168, 2015, doi: https://doi.org/10.1039/C4EE03029J.

[18] F. Ni, «How Important are Electric Vehicles for Future Copper Demand», p. 22.

[19] A. Lucas, C. Alexandra Silva, y R. Costa Neto, «Life cycle analysis of energy supply infrastructure for conventional and electric vehicles», *Energy Policy*, vol. 41, pp. 537-547, feb. 2012, doi: https://doi.org/10.1016/j.enpol.2011.11.015.

[20] S. Bumby, E. Druzhinina, R. Feraldi, D. Werthmann, R. Geyer, y J. Sahl, «Life Cycle Assessment of Overhead and Underground Primary Power Distribution», *Environ. Sci. Technol.*, vol. 44, n.º 14, pp. 5587-5593, jul. 2010, doi: https://doi.org/10.1021/es9037879.

[21] HidroCantábrico distribusión electrica S.A.U., «Especificacion tecnica de las canalizaciones subterraneas de baja y media tensión». [En línea]. Disponible en: https://www.hcenergia.com/recursos/doc/Colaboradores/Proveedores/Electricidad/Ingenieria/2116218461_2772011142751.pdf.

[22] Ministerio de ciencia y tecnología, «Guia tecnica de aplicacion- Caidas de tensión». [En línea]. Disponible en: http://www.f2i2.net/documentos/lsi/rbt/guias/guia_bt_anexo_2_sep03r1.pdf.

[23] ATS energia, «Vida útil de elementos de transmisión». [En línea]. Disponible en: https://www.cne.cl/wp-content/uploads/2018/04/informe-vida-util-ATS.pdf.

[24] ADIF, «Memoria descriptiva CA-220». [En línea]. Disponible en: https://www.seguridadferroviaria.es/recursos_aesf/1DAEAFAF-ADC0-4BFE-8958-4BC6AD3AC4F6/144042/017CA2203kV_2012.pdf.

[25] UIC, «Railway handbook 2013». [En línea]. Disponible en: https://uic.org/IMG/pdf/2013_uic-iea_railway_handbook_web_high.pdf.

[26] «UIC statistics», *UIC*. https://uic.org/support-activities/statistics/.

[27] PLASSER ESPAÑOLA, «Rendimiento, precisión y fiabilidad en la construcción de catenaria». [En línea]. Disponible en: https://www.plasser.es/pdf/publicaciones/via_libre-2008-004.pdf.

[28] USGS, «Mineral Commodity Summaries», 2015.

[29] A. Ortego, A. Valero, y G. Calvo, «MEDEAS Annex4:Task2.2.c.2.Exergy extraction curves considering non renewable resources and raw materials.» [En línea]. Disponible en: https://www.medeas.eu/system/files/documentation/files/Deliverable%202.2%20%28D7%29_Annex4_Task%202.2.c.2_Exergy%20extraction%20curves.pdf.

[30] UNEP, Ed., *Metal recycling: opportunities, limits, infrastructure: this is report 2b of the Global Metal Flows Working Group of the International Resource Panel of UNEP*. Nairobi, Kenya: United Nations Environment Programme, 2013.

[31] H. E. Melin, «State-of-the-art in reuse and recycling of lithium-ion batteries», p. 57.

[32] I. de Blas, M. Mediavilla, I. Capellán-Pérez, y C. Duce, «The limits of transport decarbonization under the current growth paradigm», *Energy Strategy Rev.*, vol. 32, p. 100543, nov. 2020, doi: https://doi.org/10.1016/j.esr.2020.100543.

[33] I. Capellán-Pérez, M. Mediavilla, C. de Castro, Ó. Carpintero, y L. J. Miguel, «Fossil fuel depletion and socio-economic scenarios: An integrated approach», *Energy*, vol. 77, pp. 641-666, dic. 2014, doi: https://doi.org/10.1016/j.energy.2014.09.063.

ACKNOWLEDGMENT

This work has been partially developed within the framework of the LOCOMOTION project funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 821105. The authors also appreciate the support of MODESLOW (Modeling and Simulation of Scenarios towards a Low Carbon Transition: The Spanish Case), a research project funded by the National Research, Development and Innovation Programme (Spanish Ministry of Economy and Competitiveness, ref. ECO2017-85110-R). The authors are members of the MENTES Network (reference of the RED2018-102794 project) funded by the Ministry of Science and Innovation of the Government of Spain.