

Selected social impact indicators influenced by materials for green energy technologies

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Saeed Rahimpour^{1,2}✉, Mohammad El-Wali^{3,4}✉, Iryna Makarava¹,
Hanna L. Tuomisto^{1,3,4,5}, Mari Lundström¹ & Andrzej Kraslawski^{2,6}

The social risks of green energy transition are underexplored. One of the important questions is which materials used in green energy technologies offer the greatest social benefits, such as ensuring decent living conditions, and which pose the most social risks. To address this issue, we develop a dynamic material-energy flow model integrating system dynamics, social life cycle assessment, and geometallurgical approaches. The analysis focuses on critical materials: Rare Earth Elements, Nickel, Silicon, Graphite, Magnesium, Gallium, Germanium, Indium, Aluminum, Cobalt, Lithium, Zinc, and Tellurium used in wind turbines, electric vehicles, lithium-ion batteries and solar photovoltaic panels. We assess their social impact on work safety, gender equality, informal employment, labor income share, employment rate, and child labor—key issues addressed by Sustainable Development Goals 1, 5, and 8. Here we show that Aluminum production for electric vehicles, wind turbines and solar photovoltaic panels generates the most jobs and income opportunities, while extraction of Cobalt, Lithium, Silicon, and Zinc carry the highest social risks.

The transition from fossil fuels to renewable energy sources has considerably accelerated in the last decade (annual increase of 16.4% of renewables¹). However, the proliferation of green energy technologies has resulted in the growth of consumption of non-renewable resources^{2,3}. Mining of those resources strongly affects the economic, environmental and social aspects of life of local communities⁴.

Economic and environmental sustainability of mining materials used by green energy technologies are intensively studied^{2,5,6}. Given the growing attention shown by previous studies to the environmental impact of green energy technologies⁷, there is also a need for quantitative assessment of the social impacts of those technologies. For example, measurement, understanding, and analysis of social sustainability of mining still require intensive research. It should be stressed that there is evident lack in the literature of quantitative analyses of the social impact of critical materials used in green energy technologies. It should be investigated carefully in order to provide a

quantitative assessment of the social consequences of mining activities and enable design and implementation of adequate policies. However, there are several challenges in defining and assessment of social sustainability of green energy technologies⁸.

Social sustainability is a broad concept that has not been precisely defined yet. The universal nature of the idea allows for its application to the specific needs and values of different communities, making it a dynamic framework for promoting the well-being and quality of life for all individuals⁹. Given the above, we must approach the energy transition with care, taking into account the needs of all stakeholders and working to minimize any negative impacts related to supply of energy materials. This phenomenon has been framed as a 'just transition' idea, even though energy transition will likely create or intensify social and environmental tensions.

Sourcing of non-renewable materials for energy transition covers their mining, processing and manufacturing. Those activities shape

¹Hydrometallurgy and Corrosion, Circular Raw Materials Hub, Department of Chemical and Metallurgical Engineering (CMET), School of Chemical Engineering, Aalto University, Espoo, Finland. ²School of Engineering Science, Industrial Engineering and Management (IEM), LUT University, Lappeenranta, Finland.

³Department of Agricultural Sciences, University of Helsinki, Helsinki, Finland. ⁴Helsinki Institute of Sustainability Science (HELSUS), University of Helsinki, Helsinki, Finland. ⁵Natural Resources Institute Finland (Luke), Helsinki, Finland. ⁶Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland.

✉ e-mail: saeed.rahimpour@aalto.fi; mohammad.el-wali@helsinki.fi

local communities in many ways, from visible changes in the physical environment to alterations of demographics and cultural characteristics. By engaging with local stakeholders, it is possible to create a shared understanding of the potential impacts of energy technologies, allowing to design and implement solutions tailored to specific needs of each community.

Achieving a sustainable future that benefits society and the environment may be possible by combining strategies that would ensure welfare maximization and minimization of environmental externalities¹⁰, e.g., by implementing policies that would guarantee energy efficiency and offer conservation incentives. Such policies could include tax credits for energy-efficient homes or appliances, subsidies for public transportation, education campaigns to promote energy-saving behaviors and implement technology policies, e.g., the use of recycled content in energy storage applications from January 2027⁶.

Many studies have evaluated the social impact of specific production technologies (e.g., the production of batteries or magnets and its impact at the local scale)^{11,12}. Several studies on the social impact of energy technology or service focus on the manufacturing stage only^{13,14}. Previous studies discussed the social impact of material usage for green energy technologies, focusing on permanent magnets¹⁵. The existing literature has also highlighted methodological challenges, high uncertainty, and lack of knowledge about the social impact of critical materials production^{16,17}. Supplementary Table 1 summarizes the investigation of the social impact of green energy technologies. The table compares various aspects of the previous studies, including information on the objectives of the study, the method used, the supply chain scope, social indicators, and geological scope.

A comprehensive quantitative study of the social impact of green energy technologies and relevant awareness of critical materials' mining, processing, and production at the global scale is still missing. Improving the social sustainability of the material lifecycle brings gaining trust and acceptability to energy-related industries. That is why a series of recently published articles², emphasized environmentally and socially sustainable ways of sourcing raw materials required for energy transition. The research gap in the literature clearly shows a need to trace the social risk (i.e., the exposure to adverse consequences stemming from human activities) related to use of critical materials required for energy transition. This study covers a comprehensive social assessment addressing the mentioned issues. The assessment includes six impact categories. Four of them directly affect the workers stakeholder, such as work safety, gender equality, informal employment, and labor share. The remaining two, employment and child labor, influence the local communities socially and economically. The assessed social indices directly correspond to specific targets aligned with the social Sustainable Development Goals (SDG) adopted by the United Nations¹⁸ with a view to end discrimination, ensure sustainable economic growth, fair income distribution, full employment, eradicate child labor, and provide safe working environments for all workers.

This work discusses three major goals associated with mining, processing and manufacturing, i.e., SDG 1: no poverty, SDG 5: gender equality, and SDG 8: decent work and economic growth. The assessed social indices are: gender equality which directly aligns with the objectives of SDG 5 (aiming to end discrimination and ensure equal participation and opportunities in leadership and decision-making); informal employment which is relevant to the objectives of SDG 8 (aiming at sustainable economic growth, full and productive employment, and decent work for all) and SDG 1 (targeting implementation of nationally appropriate social protection systems and measures for all); labor income share is directly relevant to SDG 8 objectives (ensuring a fair and equitable distribution of income between labor and capital); employment rate is directly relevant to the objectives of SDG 8

(achieving full and productive employment); child labor is addressed explicitly in Target 8.7 of SDG 8, which calls for immediate and effective measures to eradicate forced labor, end modern slavery and secure the prohibition and elimination of the worst forms of child labor; and work safety is directly relevant to objectives of SDG 8 (calling for safe and secure working environments for all workers by 2030).

The assessment addresses the mentioned social issues related to mining and processing of critical materials^{19,20} used in wind turbines, solar photovoltaics panels (PVs), lithium-ion batteries (LiBs), battery electric vehicles (EVs), hybrid EVs, and plug-in hybrid EVs. In this study, mineral processing is conducted at the site of the mine including comminution, e.g., crushing and flotation. The analysis focuses on following critical materials: Rare Earth Elements (REEs), Nickel (Ni), Silicon (Si), Graphite, Magnesium (Mg), Gallium (Ga), Germanium (Ge), Indium (In), Aluminum (Al), Cobalt (Co), Lithium (Li), Zinc (Zn), and Tellurium (Te). Our material selection decision for the energy product life cycle was based on several criteria. While considering the functional performance, as well as the economic, social, and environmental impacts of material flows, we selected materials (REEs, Ni, Si, Graphite, Mg, Ga, Ge, In, Al, Co, Li, Zn, and Te) mainly according to their supply risk factor and technological relevance (importance to energy systems). Selected materials are essential for key renewable energy technologies such as wind turbines, EVs, batteries, and solar PVs. The substantial growth in demand for these materials due to the transition to renewable energy was investigated in several studies²¹. Therefore, the materials were chosen due to the significant role they play in current and emerging technologies and their vulnerability to supply disruptions.

The comprehensive analysis of the social issues involved in energy transition supports decisions on adopting sustainable measures associated with energy sources made at the national, regional, and global levels.

In this work, our quantitative analysis provides an insight into the following questions: (i) to what extent does green energy transition—with focus on the above mentioned critical materials—contribute to increasing employment rates, female workers participation in the labor market and labor income by country, (ii) to what extent does green energy transition contribute to mitigating informal employment, occupational accidents and child labor, and (iii) which green energy technology is the most promising from the perspective of achieving social sustainability and which is the least? Answering these questions allows us to fill key knowledge gaps concerning the social aspect of global energy transition. This study identifies the materials used in green energy technologies that offer the greatest social benefits and those with the highest risks.

Results

Social impacts of mining and processing of energy materials

Figure 1 presents the positive social impacts of the mining and processing stages of the critical energy materials (i.e., critical materials used in green energy technologies) supply chain, including the employment rate of each country, labor income as part of Gross Domestic Product (GDP), and the number of female workers between 2010 and 2030. In this study, employment related to use of critical energy materials in green energy technologies is analysed mainly in exploration, mines and processing plants construction, and operations and processing of materials.

Employment rate

The results show that in 2010 the highest employment rate in mining and processing stages of the investigated critical energy materials for green energy was reported in Zambia (~38%), followed by Russia (~17%), Australia (~14%) and other countries in which the rate was below 10% of the country's population. Australia will reach the

employment rate in the mining sectors of studied materials ~35% in 2030, followed by Russia with ~28%, Brazil (~23%), Canada (~18%), the US (~12%), Chile (~10%) and other countries remaining below 10%. Mining-related job growth can contribute to the development of the community, knowledge, innovations, and opportunities for skills improvement. It is worth noting that between 2004 and 2013 Australian mining industries created at least 122 thousand mining construction jobs, compared with 34 thousand operational jobs and 13 thousand exploration-related jobs²².

There is a severe imbalance in the employment situation for the Democratic Republic of Congo (DRC)—which is No. 1 producer of cobalt globally—due to the lack of a proper policy for youth employment. The country has a high unemployment rate of 73%, and around 80% of the population operates in the informal sector. In the DRC, workers employed by subcontractors earn substantially less than those hired directly by the mining companies, and most (~63%) do not earn a living wage (\$402 per month)²², the minimum remuneration to afford a decent standard of living.

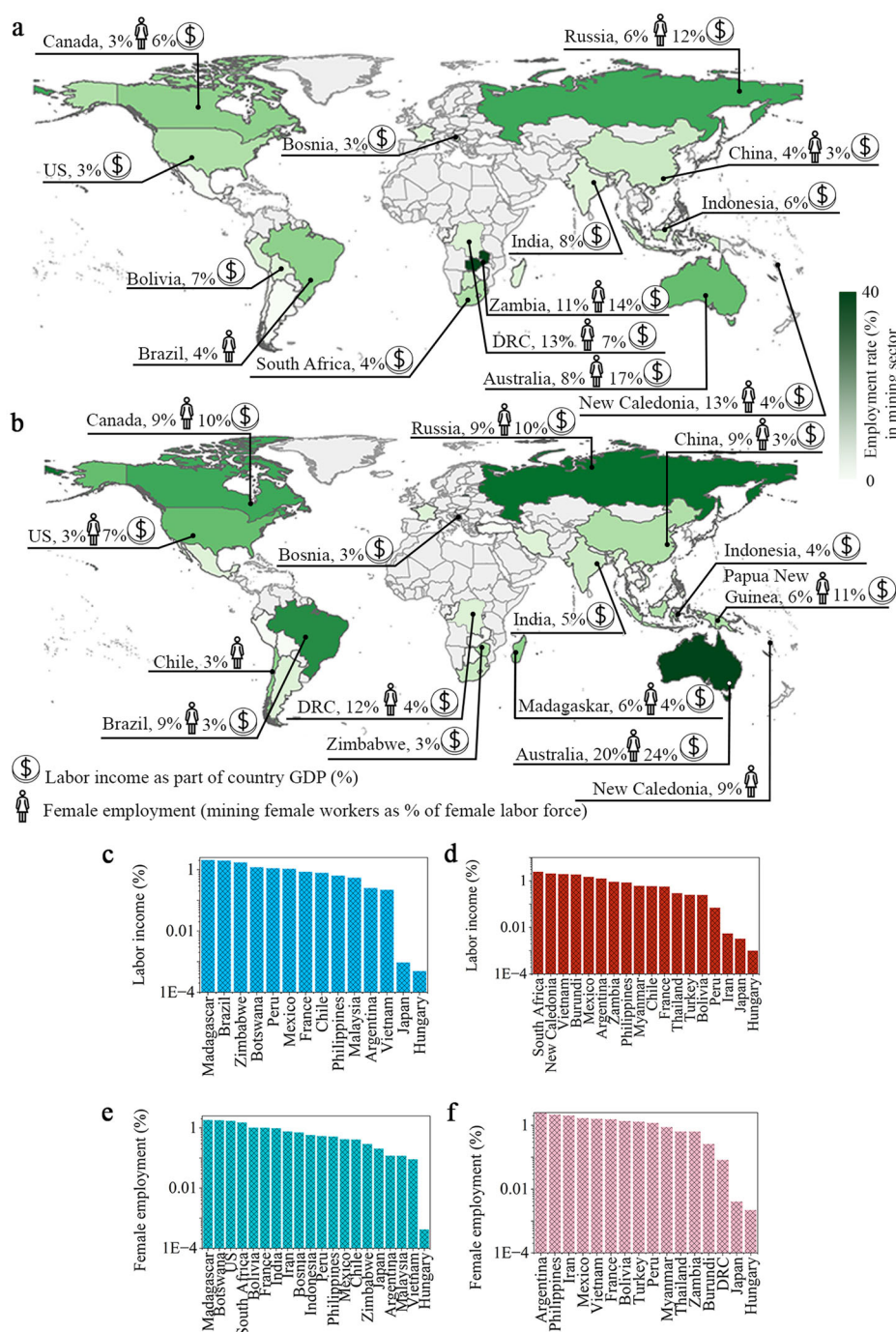


Fig. 1 | Employment rate, labor income, and female workforce participation in the mining sector of critical energy materials. Comparison of employment rate in the mining sector (top producers), labor income as part of GDP, and rate of female workers in the mining of critical energy materials as a percentage of the total female workforce by country in (a) 2010 and (b) 2030; (c) low labor income from

the mining sector by country in 2010; (d) low labor income from the mining sector by country in 2030; (e) countries with a low share of female working in the mining sector in 2010; (f) countries with a low share of female working in the mining sector in 2030.

Labor income share

The substantial increase in mining investment and/or mining of the high-demand minerals from emerging economies, continue to have important macroeconomic impacts. In addition, higher labor income can stimulate economic growth and create job opportunities. According to the World Bank²³, the categorization of world countries based on income levels is based on the three income categories, where low-income economies are those with a gross national income (GNI) per capita equivalent to or less than \$1145, middle-income economies are those with a GNI per capita between \$1146 and \$4515, and high-income economies are those with GNI per capita between \$4516 and \$14,005. The results show that Australian mining industries will provide the highest global labor income as part of GDP (-24%) in the whole period between 2010 and 2030. The highest labor income estimated for Australia in 2030 corresponds to mining lithium (-6.7%) and nickel (-5.5%), among other elements one can list REEs, silicon, aluminum, cobalt, and zinc. Other countries with significant share of labor income from mining activities of studied materials as part of GDP include Papua New Guinea (-11%), Russia, and Canada (-10%). Interestingly, all high labor-income countries are counted as one of the primary producers of cobalt—Russia (2nd), Australia (3rd), Canada (5th), and Papua New Guinea (7th). Given the economic importance of mining, Russia has a very important role to play in providing several critical materials for energy-related industries, including REEs, Ni, Si, graphite, Mg, Ga, Ge, Al, Co, and Zn. However, trade sanctions against Russia have exposed the vulnerability of global supply chains of those critical materials and the need for diversification and resilience in sourcing these essential resources.

Increasing investment in mining will lead to increases in income from mining activities and accelerate the need for improved infrastructure (e.g., roads, railways, ports, and energy facilities) to service mining sites (e.g., the extraction, transportation, and processing of mined materials). This can trigger the development and enhancement of infrastructure in regions where mining activities are taking place. Also, the expansion of mining accelerates population growth, which will add to the economic momentum. Hence, the opening and closing of mines directly influence changes in the studied indicators. The detailed calculations show the increase of labor income caused by the (re)opening of mines for extracting REEs in 2020 for Australia (-6%), Burundi (-2.5%), Madagascar, Myanmar, Thailand, the US, and Vietnam (-1%). The same has been observed as a result of the opening of a magnesium mine in Iran (-0.1%), cobalt mines in Mexico and the US (-1%), and lithium mines in Papua New Guinea (-21%), Turkey (-0.3%), and Canada (-1.5%). Closing the REEs mine in Malaysia, cobalt mine in Botswana, and zinc mine in Bolivia caused -1% decrease in their total labor income. Similarly, the same phenomenon was observed in South Africa with the closing of a silicon mine, which caused a 3% decrease in the total labor income. Also, it is estimated that population growth decreases labor income as part of the country's GDP by between 1 and 3%.

Gender equality

Share of female workers in the mining sector of critical materials used in green energy technologies in 2021 was between 10 and 20% out of the share of female in the total workforce ranging between 41 and 50%. In 2010, The highest female employment rate was reported for the DRC and New Caledonia (-13%), and Zambia (-10%). However, Australia (-20%) became a leader in the female employment rate in 2020 and is estimated to remain one in 2030, followed by DRC (-12%) and China (-9%). While there have been growing attempts to guarantee fair involvement and benefits for female in large-scale mining, obstacles continue to exist. Less than 10% of the global large-scale mining workforce corresponds to female employment and they face lower pay and gender discrimination²⁴.

Minerals extraction have contributed to several adverse impacts, such as population displacement, violent conflicts, and human rights violations²⁵. Here, we analyze two significant indicators, such as informal employment and child labor, related to the production of critical materials for green energy.

Informal employment

Social risk challenges become more substantial when regulatory safeguards are inadequate and systemic problems such as labor informality, weak fiscal capacity, and inequalities are persistent, like in artisanal and small-scale mining. Unfortunately, a significant number of children (within the age range of 5–17 years old) and adults (within the age range of 24–64 years old) are engaged in the mining workforce via informal employment. In artisanal mining, activities are informal or illegal, as individuals are not be able to obtain an exploitation permit via a system designed for large companies²⁶. Figure 2 shows a considerable proportion of informal employment in the period 2020–2030, which is estimated to increase as a result of the production of REEs (from -1.5 to -6.2%), nickel (from -2.6 to -5.6%), graphite (from -3.8 to -7.1%), cobalt (from -55.4 to -68%), and lithium (from -2.3 to -16.8%). The results demonstrate that in 2020 a significant percentage of the workforce were employed under informal arrangements in several countries, which may affect social and economic conditions. For example, countries heavily resorting to informal employment include Madagascar in REEs and graphite mining, Indonesia in Ni mining, Bosnia in Si mining, Chile and Zimbabwe in Li mining, Bolivia and Peru in Zn mining, DRC and Zimbabwe in Co mining. Also, it is estimated that without changes in current policies, several countries will continue to have a significant percentage of their workforce engaged in informal employment by 2030, i.e., Madagascar in REEs and graphite mining; Indonesia in Ni mining; Bosnia in Si mining; Russia in graphite and Zn mining; Argentina, Brazil, Chile, and China in Li mining; Zimbabwe in Li and Co mining; Bolivia in Zn mining and DRC in Co mining.

Child labor

Child labor can severely affect health, education opportunities, and overall well-being. In the mining and processing stages, as shown in Fig. 3, the highest child labor percentages are reported for Zambia (-15% in cobalt mining), Zimbabwe (-6% in cobalt mining), South Africa (-2% in cobalt and silicon mining), DRC (-1% in cobalt mining), Chile (-1% in lithium mining), and other countries <1%. Given the current policies, it is estimated that this adverse trend will exacerbate for Zimbabwe, which will exceed 20% of the share of child labor, followed by Madagascar (-4%, with increasing production of REEs, graphite, and cobalt) in 2030. Among the list of investigated critical energy materials, graphite and lithium, followed by cobalt and silicon, exhibited the most dramatic changes in addressing the child labor issue. In 2020, Madagascar effectively met the social target for eliminating child labor in graphite mining. However, it is predicted that child labor will increase along with the intensification of graphite mining by 2030, generally. Similarly, Zimbabwe may intensify resorting to child labor following the increase in lithium mining by 2030, leading to values below the threshold levels stated in the SDGs (Fig. 3). Addressing these issues requires concerted efforts from governments and international organizations aimed to enforce regulations, improve working conditions, and provide alternative opportunities for these children.

Work safety

The risk of accidents in mining and processing is very high and can be mainly classified as environmental-related accidents, equipment-related accidents, person-related accidents, and other accidents. Several studies have already investigated and quantified the severity of occupational accidents in the mining sectors^{27,28}. In this study, we analyzed occupational accidents associated with the manufacturing of

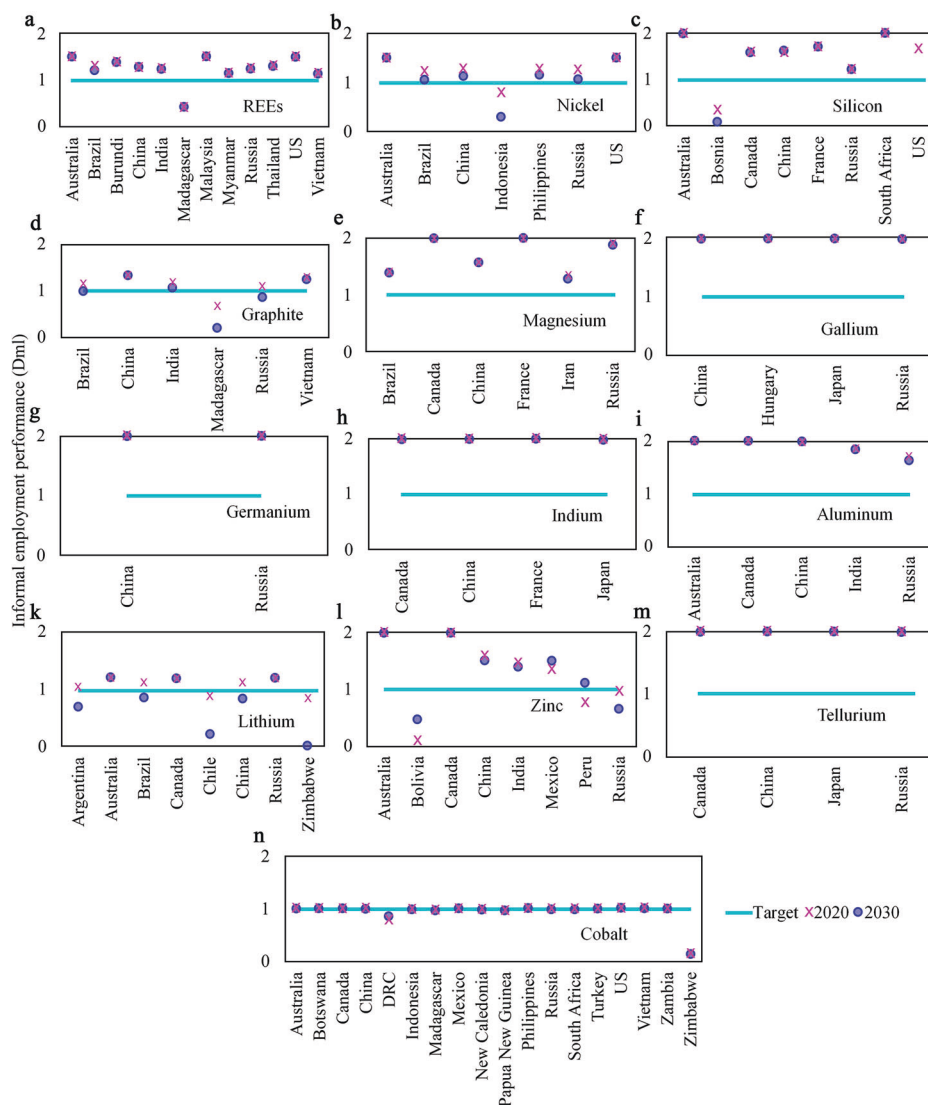


Fig. 2 | Informal employment trends in mining and processing stages of critical energy materials by top producer countries. Informal employment performance in mining and processing (mineral processing at the site of the mine) stages by top producer country between 2020 and 2030 relative to the threshold level (i.e., standard or benchmark for acceptable levels of informal employment by SDG) as a result of production of (a) Rare Earth Elements (REEs), (b) Nickel, (c) Silicon, (d)

Graphite, (e) Magnesium, (f) Gallium, (g) Germanium, (h) Indium, (i) Aluminum, (j) Lithium, (k) Zinc, (l) Tellurium, (m) Cobalt. Stars indicate informal employment levels for the country in 2020. Open circles represent the estimated informal employment in 2030. The horizontal blue line represents the social threshold for sustainable development goals. Values above the social threshold mean successes in eradicating informal employment and vice versa.

wind turbines, EVs, LiBs, and solar PVs. According to our findings, the number of occupational accidents will increase with the increases in demand for renewable energy technology. By 2030, accident rates for wind turbines, EVs, and LiBs are expected to be 2–2.2 times higher than the current ones. In 2030, the share of occupational accidents in solar PV manufacturing is expected to increase by 69% compared to current rates. This increase is primarily due to low accident rates in the countries with the highest share of employment in the solar PV industry.

Social impacts of energy materials at global scale

The propagation of green energy technologies create employment opportunities, increases opportunities for achieving gender equality, stimulates economic growth, and can contribute to the development of local communities. However, it also contributes to negative social impacts, such as child labor, informal employment and issues related to work safety. We studied the global impact of mining, processing and use of critical materials in selected technologies (wind turbines, EVs,

batteries, and solar PVs) on a several social indicators (Fig. 4). Globally, the implementation of the mentioned green technologies could improve job opportunities and the participation of women, potentially leading to 1.8 times increase in employment rates by 2030. The development of these technologies is expected to raise the overall labor income in the energy sectors by 1.6 times in 2030, driven by increased demand for new job opportunities. However, this paradoxically will also exacerbate problems in other social areas, as the advancement of these technologies is predicted to raise the incidence of informal employment by 1.7 times and child labor by 1.9 times in 2030.

In general, solar PV industry development will have the highest positive social impact through the highest contribution to the global employment rate and female employment participation (0.15%), as well as the total labor income as part of country GDP (0.09%) in 2030.

The findings regarding LiBs indicate that earlier (2010) global cobalt production had the most significant effect on the employment, accounting for -98% of all investigated elements. This percentage is

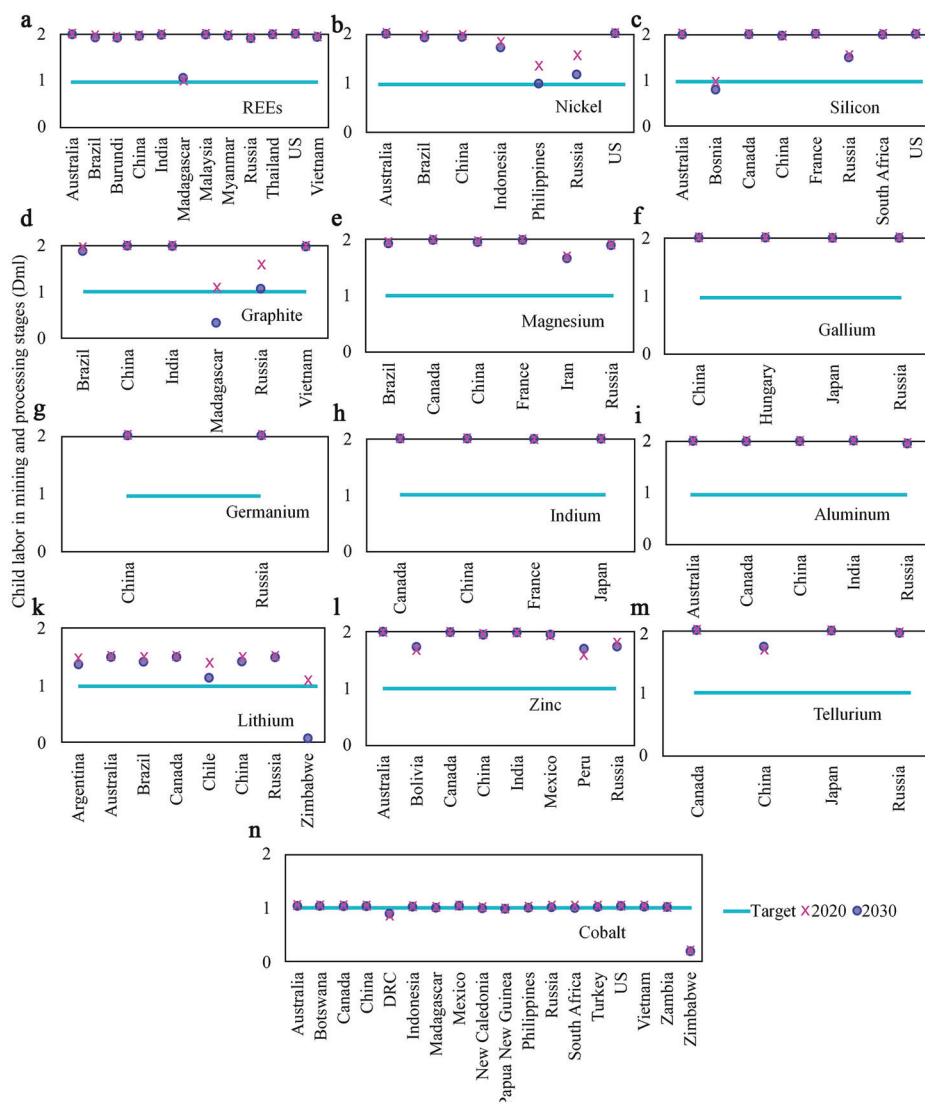


Fig. 3 | Child labor trends in mining and processing stages of critical energy materials by top producer countries. Child labor in mining and processing (mineral processing at the site of the mine) stages by top producer country between 2020 and 2030 relative to the threshold level (i.e., standard or benchmark for acceptable levels of child labor stated in SDGs) as a result of production of (a) Rare Earth Elements (REEs), (b) Nickel, (c) Silicon, (d) Graphite, (e) Magnesium, (f)

Gallium, (g) Germanium, (h) Indium, (i) Aluminum, (k) Lithium, (l) Zinc, (m) Tellurium, (n) Cobalt. Stars indicate child labor performance for the country in 2020. Open circles represent the estimated child labor levels in 2030. The horizontal blue line represents the social threshold concerning sustainable development goals. Values above the social threshold demonstrate progress in eradicating child labor and vice versa.

estimated to decrease to around 79% by 2030. Following cobalt production, the impact of lithium production accounted for -19%, with the remaining elements representing around 3%. Results for EVs show that in year 2010 cobalt production accounted for -32% of the impact on the employment rate, while lithium production contributed around 23%. It must be noted that social risks for cobalt processes are higher compared to the production of other elements. This could be mainly due to geopolitical issues like instability, conflicts, or governance issues in cobalt-producing regions like DRC. Also, excessive water consumption in lithium production (around 65% of resources are located in medium to very high-water-risk areas²⁹) leads to water scarcity in local communities, affecting access to clean water for drinking, agriculture, and sanitation. This results in social challenges such as health issues, food insecurity, and economic problems for the affected communities. Additionally, environmental degradation caused by high water consumption can disrupt ecosystems, potentially leading to the displacement of communities and loss of livelihoods, further exacerbating social vulnerabilities. It is estimated that due to

the growing production of lithium required for electric vehicles, the impact of elements production on the employment rate will be for Li around 81% in 2030, followed by Zn (-8%), Co (-5%), Ni (-4%), and graphite, Mg, Al, and REEs taken together (less than 2%) of the total share of critical materials used in EVs.

The results for solar PVs show that in 2010, silicon production had an impact on the employment rate representing -99% of the total share of materials used in PVs (Ga, Ge, In, Al, and Te) and was estimated to decrease to 97% in 2030, mainly because of the development of new PV technologies rather than monocrystalline and polycrystalline silicon PVs. Considering wind turbine technologies, in 2010 the impact of zinc production on the employment rate represented -83% of the total share of materials used in wind turbines, followed by REEs (-9%), nickel (-8%), and aluminum (<1%). It is estimated that zinc production impact on employment rate will drop to 60% of the total share of materials used in wind turbines, while REEs and nickel production impact will increase respectively to -29% and -11% in 2030.

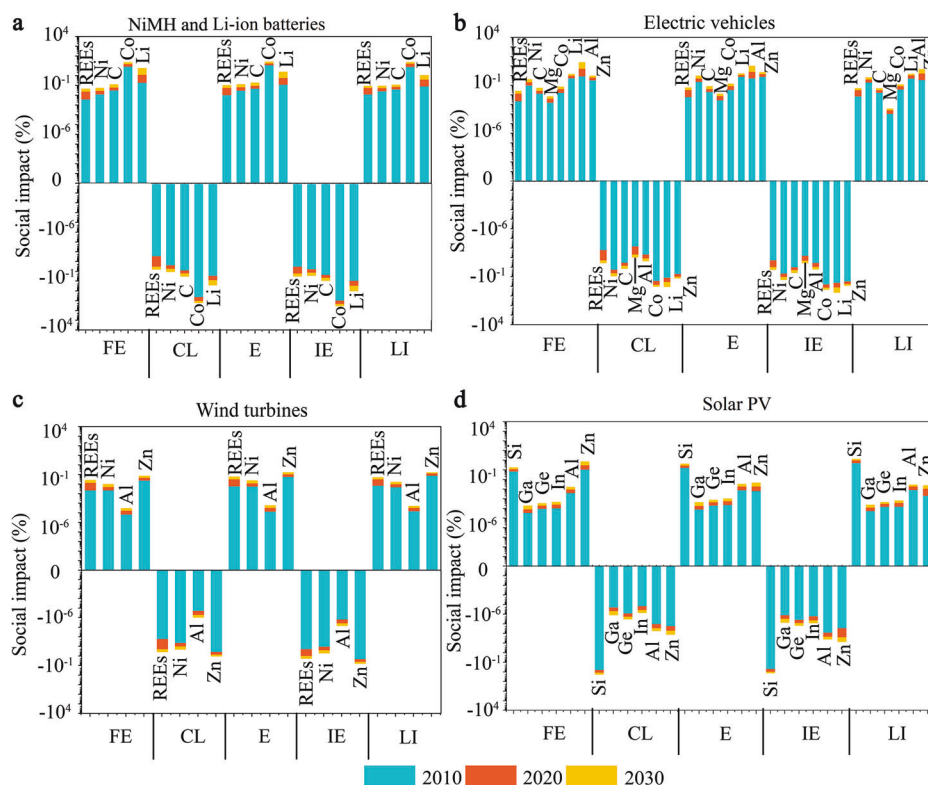


Fig. 4 | Impact of materials used in energy technologies on selected social indicators. Impact of critical energy materials on selected social indicators based on four applications (a) Nickel-metal hydride (NiMH) and Li-ion batteries, (b) EVs, (c) wind turbines, (d) solar PVs from 2010 to 2030. Social indicators include FE – Female employment (as a percentage of female workforce); CL – Child labor (as a

percentage of child population); E – Employment rate (as a percentage of country workforce); IE – Informal employment (as a percentage of total employment in a country); and LI – Labor income as part of country GDP in percentage. The calculations include mining, processing (mineral processing at the site of the mine) and manufacturing sectors.

Calculations show that the employment rate for mining industries is expected to increase 10–15 times by 2030 due to the growing production of REEs, Si, Mg, Ga, Ge, Zn, and Te, compared to 2010. Considering labor income in mining industries as part of the national GDP in countries covered by our study, around 97% of the increase in labor income is attributed to mining activities related to cobalt, zinc, silicon, nickel, graphite, REEs, and lithium. Additionally, processes related to cobalt mining alone generate ~40% of the total labor income among all these metals and non-metals. The most significant change in labor income for mining industries is expected for lithium mining, from -1.9 to -16% of the total labor income for Li producers (i.e., Argentina, Australia, Brazil, Canada, Chile, China, and Zimbabwe) in the years 2010–2030. This is affected by the growth of employment rate in lithium mining industries from -2.7 to 42% of the total employment rate for Li producers and positively influencing female employment rate in mining industries. A decrease in labor income in mining industries will be caused by zinc and silicon mining (-5% in 2030 cf. -13% of the total labor income for Zn and Si producers (Australia, Bolivia, Canada, China, India, Mexico, Peru, Russia, Bosnia, France, South Africa, and the US) in 2010). The analysis shows that labor income thanks to nickel mining will increase by ~3% of the total labor income for Ni producers (from -10 in 2010 to -13% in 2030). It shows minimal impact of nickel production on the total labor income, considering the growing demand for batteries.

It is estimated, that if mining is not managed sustainably, the probability of increased incidence of child labor will grow from 0.1 to 1.3% of the global child labor in mining due to REEs production, from 1 to 2.3% due to Ni production, from 1.3 to 2.7% due to graphite production, from 0.1 to 0.5% due to Mg production, and from 0.6 to 4.1% due to Li production, over the period 2010–2030.

From an economic perspective, reducing gender gaps in workforce participation could substantially boost global GDP. Mining is one of the most male-dominated industries, with female making up only 5–15% of workers. The results show that female employment increased in the years 2010–2030 thanks to the production of REEs (from -1.6 to -8.7% of the global mining female workforce), Ni (from -5 to -10.3%), graphite (from -5 to -9.4%), Mg (from -1.7 to -3.1%), Li (from -1 to -18%), and Te (from -0.7 to -2.6%).

If not managed correctly, putting new energy technologies in place can result in considerable social, economic, technical, and ecological problems³. Sustainable use of resources and energy system services can reduce risks and contribute towards securing equity and justice for future generations. Several studies call for more social assessment in energy research and addressing issues pertaining to, e.g., justice³⁰, ethics³¹, fairness³², and history³³. This article aims to ensure that the social benefits of mineral resources used for energy technologies reach out to all people while safeguarding the future of the environment.

We tested the implications of hypothesized causal relationships between population growth and associated social indicators, i.e., employment rates and child labor. Our uncertainty analysis covers policy studies exploring distributive justice concerning selected critical raw materials, emphasizing the challenges created by the global operating environment changes that may impact the solutions adopted at national level. The dynamics of the world population and labor force depend on several social and demographic factors, i.e., mortality rate, fertility rate, replacement rate, and immigration rate. We explored the impact of the several population and labor force projection scenarios on the relevant social indicators associated with mining critical raw materials, i.e., employment rates and child labor. In

addition to the medium variant projection (baseline), other projection scenarios developed by the United Nations³⁴ were considered to assess the uncertainty for the child labor in the mining of critical raw materials, i.e., high variant, low variant, constant fertility, instant replacement, instant replacement with zero migration, momentum, zero migration, constant mortality, and no change scenarios. The uncertainty of the employment rates in critical raw materials sector was assessed by applying momentum, zero migration, and constant mortality population scenarios—in addition to the medium variant (baseline). Medium variant scenario refers to the best estimate of future population trends. High and low variant scenarios refer to higher and lower fertility rates than the medium variant. The constant fertility rate scenario projects population growth based on fixed fertility rates that do not change over time. The instant replacement scenario refers to the population growth if fertility rates were to adjust to the replacement level. The zero migration scenario refers to population growth without international migration from and to the country.

Child labor in mining critical raw materials was the most affected, where instant replacement and momentum projection scenarios could exacerbate child labor percentage in some countries (i.e., Burundi, Congo) by at least 0.35 times the baseline population scenario. The same population scenarios (i.e., instant replacement and momentum) led to lower child labor percentage in several countries, i.e., China, Thailand, Brazil, Bosnia, and Chile by at least 0.1 times compared to the baseline population scenario. The employment rate in mining critical raw materials was also affected by the changes associated with labor force projections, where changes reached up to 5% compared to the medium variant projection scenarios. The detailed uncertainty analysis results can be found in Supplementary Table 4 and Supplementary Data 1 section, sheets 58–85.

Discussion

Energy transition is vital to overcome the climate crisis resulting from using non-renewable energy sources. Rapid diffusion of green energy technologies necessitates greater quantities and wider variety of minerals. The social interface of extractive operations is complex, dynamic, and non-linear³⁵. Addressing these complex relations requires a holistic approach that takes account of interactions among several stages of material supply chains.

Social risks that may be associated with the development of green energy are triggered by two situations: (i) choices that we can make based on known parameters, and (ii) decisions that have to be taken under conditions of imprecise or even missing information (known unknowns), and thus without knowing the proper parameters. This study incorporates risks inferred from historical data into the first phenomenon. Once certain social thresholds are exceeded according to SDGs, several systematic challenges might interact due to feedback mechanisms of energy systems. For example, changes in employment and income influence community stability.

The social benefits of renewable energy are manifold, as shown in the results: doubled contribution to the employment rates and female participation in the labor market by 2030, as well as 1.5 times higher total labor income as part of the GDP of individual countries. Despite the advantages that productivity improvements may bring into the emerging green technologies, it can affect the size of workforce needed, as fewer workers could be able to produce the same amount of output. Hence, this might impact employment rates, and by extension, total labor income as part of country GDP. The findings suggest that improved performance of the solar PV industry will contribute the best to the social performance of countries (i.e., employment rates, female participation, and labor income as part of the country's GDP) compared with other green energy technologies (LiBs, EVs, and wind turbines). These benefits align with SDG 1, SDG 5, and SDG 8, which are essential for energy transition. Although the negative social externalities from the

mining industry may be fewer than those from the fossil fuels industry, there is still room for many improvements.

It should be noted that any failure in mining operations creates risks to all stakeholders involved in the industry, as well as regions, and communities. There is a need for sustainable management of process selection concerning the feed properties, waste management of the separated radioactive elements, and how they can be treated to produce valuable co-products. For example, the failure of mine tailing storage facilities caused some of the most serious environmental disasters in history³⁶.

REEs contain significant amounts of radioactive materials such as uranium, thorium, and products of their decay. These materials generally do not pose great harm when isolated under the earth's surfaces. However, once they are exposed to an environment with high concentrations associated with REE mining, radioactivity becomes an issue that needs to be tackled². The exposure of these radioactive materials happens during the beneficiation processes, affecting primarily workers in close contact. This leads to hazardous occupational accidents³⁷.

Furthermore, a careful choice of manufacturing locations is crucial for understanding and addressing the social impacts linked to the development of energy technologies. For example, the projected increase in the manufacturing of solar PVs, and the current regional distribution of manufacturing sites in countries leaning towards higher salaries and wages, and women's involvement in economic activities affected positively solar PV technologies performance in meeting social criteria. In this line, analysis indicated that solar PVs production has the highest effect on all studied social indicators, followed by EVs, wind turbines, and LiBs. Among other energy technologies, the development of solar PV technology is expected to rise the most (6 times), from around 1000 GW in 2022 up to 6000 GW by 2030³⁸. Wind power technology is anticipated to reach the capacity of 3000 GW by 2030, up from around 910 GW in 2022³⁸.

The results demonstrated that green energy technologies could increase employment rates and female participation by 1.8–1.9 times in 2030 compared to the current data for manufacturing turbines, EVs, LiBs, and solar PVs. Similarly, the total share of labor income as part of country GDP showed an increasing trend with the projected development of green energy technologies to be up to 1.5 times higher by 2030 than the actual data.

Interestingly, the results show that the increase of aluminum production would be beneficial for several social sustainability indices. It is observed that the production of aluminum for EVs, wind turbines and solar PVs create the most jobs and income opportunities. On the other hand, it is well known that the aluminum production is one of the most polluting industrial processes^{39,40}. This situation illustrates the existence of possible conflicts between some social and environmental indicators.

It is worth noting that the worsening of social risks linked to critical materials (e.g., cobalt, lithium, silicon, and zinc) is propelled by the expansion of mining operations in areas where these social risks already exist. This includes countries such as Zimbabwe, Zambia, Bolivia, and Bosnia. Several social issues, i.e., child labor, informal employment, and occupational accidents intensify with the development of green energy technologies by 1.8 times, 1.6 times, and 1.2 times, respectively, compared with the current situation in the manufacturing of green energy technologies. The recommended steps to lower the social risks of green technologies start by addressing the upstream where mining and processing activities take place. Also, the substitution of relatively high social risks materials such as Co, Li, Si, and Zn for green energy technologies will help to cope with the challenges for a just transition.

The findings of this study highlight the need for a robust and integrated system of social information and statistics to clearly understand the size of the social impacts linked to the mining materials

and manufacturing energy technology sectors. We call for critical evaluation of existing frameworks, methodologies, criteria, and indicators to assess the social impact of energy transition through all stages of the supply chain and analyze the current and future embedding and interlinking of material-energy activities. To identify the bottlenecks and constraints that may jeopardize the social sustainability of renewable energy transition and facilitate the social license to operate, it is essential to provide a framework for classifying the social impacts of critical materials resources used in energy transition. This can be based on a review of the existing approaches and interaction with other dimensions of natural resource classification to identify strengths, weaknesses, similarities, differences, and gaps. We need to be aware of potential direct and indirect social impacts of using different materials and chemical processes in the renewable energy transition—predict the significance of social impacts over specific time and geographical application. It should be noted that location has a significant impact on the overall social impact of material processes. For example, the PV supply chain is currently located in regions where the decarbonization of the electrical grid is expected to be slower than in other regions, especially in the US as shown in more detail within the 2017 National Renewable Energy Laboratory (NREL) technical report^{41,42}.

The social assessment provided in this study can be harmonized with technological advancements and increased market penetration of renewable energy sources. To implement the dynamic model proposed in this study, it is recommended to have an action-based research approach to studying the social consequences of material-energy system change. In this line, the continuous interaction of supply chain stages with their environment should be evaluated. The proposed model aims to estimate the utility of the concept(s) applicable to action in the current energy systems context, engage in practical action, and adopt any new social concepts that emerge: a largely material-energy cycle through their lifetime. The proposed model can be used as a reference for policymakers to understand the social impact of renewable energy transition. This multidisciplinary study is vital to understanding the underlying practices, relationships and politics within complex social-ecological systems, and the trade-offs of energy transition actions. The study evaluates the social impact of renewable technologies development focusing on the selected critical raw material requirements of the green transition. In line with this study, it is suggested to investigate socio-economic and environmental impacts of energy transition to generate benefits beyond energy solutions to deliver multiple advantages to society.

Methods

The model introduced in this study used a system dynamics method with social life cycle assessment. Also, we considered geometallurgical approach integrated with processing routes analysis for the material flow analysis. Using system dynamics modeling⁴³, we quantified the mass flow analysis and key social indices in mining and processing of materials required by green energy technologies as well as manufacturing of equipment used by those technologies, such as wind turbines, electric vehicles (EVs), lithium-ion batteries (LiBs), and solar photovoltaic panels (PVs). We quantified the key social indices of the related critical materials, i.e., Rare Earth Elements (REEs), Nickel (Ni), Silicon (Si), Graphite, Magnesium (Mg), Gallium (Ga), Germanium (Ge), Indium (In), Aluminum (Al), Cobalt (Co), Lithium (Li), Zinc (Zn), and Tellurium (Te). We conducted an uncertainty analysis to examine the validity of the designed model. The results showed at least 97% compatibility of simulation model results with real-world data. This included REE mining and production of the solar PVs. Details on the analysis can be found in Supplementary Data 1.

The analysis of the social impact of supply chains starts by identifying the related stakeholders. Lifecycle stakeholders are entities for

which social consequences are most likely to occur⁴⁴. In this study, the analysis follows the cradle-to-gate approach, where the system boundary covers the extraction of raw materials until the manufactured energy technologies are produced and ready to be utilized. In this study, the workers stakeholder corresponds to the group of individuals engaged in direct economic activities along the supply chain. The local communities stakeholder corresponds to the group of people residing or living in a common location and sharing the same geographical locations where the supply chain processes occur⁴⁵.

Each stage of the supply chain reflects a hotspot where certain social issues are most likely to materialize. The impact of these issues affects relevant stakeholders⁴⁶. Unlike the other types of assessments, e.g., environmental assessments, social assessment in this study covers positive and negative social impact categories (Table 1).

This study proposes a dynamics model covering regional flows of critical materials covered by the study and their use in the manufacturing of analyzed green technologies. The model consists of 1182 variables and parameters. The main variables, including flow, stock and auxiliary variables, are presented in Supplementary Table 2; parameters and all data required to run the model are available in Supplementary Table 2 and Supplementary Data. To specify model boundaries (Supplementary Fig. 1), we divided the variables of the dynamic model into two groups, including endogenous and exogenous variables. Endogenous variables affect and, at the same time, are affected by other system components and parameters, while exogenous variables are not directly affected by the system. Groups and types of all variables are presented in Supplementary Table 2 and 3. The dynamic assessment of the social indicators is dependent on the three main factors: (1) geographical location (country or region where the processes take place), (2) life cycle stage (mining, processing, and manufacturing), and (3) the technology processed in addition to the related critical energy materials needed (Fig. 5). The analysis covers social assessment of all stages of the supply chain. We assessed the manufacturing stage for six technologies, i.e., wind turbines, solar PVs, LiBs, battery EVs, hybrid EVs, and plug-in hybrid EVs.

Stocks and flows are the foundations of system dynamics modeling (Supplementary Eqs. 1 and 2). Stock (i.e., stock of material or energy) corresponds to an entity that accumulates or drains over time, as shown in Eq. (1).

$$\mathbf{S}(t) = \int_{t_0}^t [\mathbf{I}(t) - \mathbf{O}(t)] dt + \mathbf{S}(t_0) \quad (1)$$

where, $\mathbf{S}(t)$ is the amount of material accumulated at time t ; $\mathbf{I}(t)$ and $\mathbf{O}(t)$ are calculated using Eq. (2). $\mathbf{I}(t)$ is the amount of material input to $\mathbf{S}(t)$ at time t ; $\mathbf{O}(t)$ is the amount of material output from $\mathbf{S}(t)$ at time t ; and $\mathbf{S}(t_0)$ is the amount of material accumulated at the initial time t_0 .

$$\begin{aligned} \mathbf{I}(t) &= \mathbf{f}(\mathbf{S}(t), \mathbf{V}(t), \mathbf{P}); \\ \mathbf{O}(t) &= \mathbf{f}(\mathbf{S}(t), \mathbf{V}(t), \mathbf{P}) \end{aligned} \quad (2)$$

where $\mathbf{V}(t)$ is an auxiliary variable (i.e., it is not directly affected by the system components) at time t , e.g., the supply flow of materials depends on the available amount of resources and production capacity; $\mathbf{P}$ is a parameter of the system, e.g., processing coefficient of energy materials to manufacturing stage.

Social life cycle assessment consists of impact categories and sub-categories of social dimension which we explain separately.

Gender equality

Equal rights are crucial for sustainable development and economic growth⁴⁷, which aligns with SDG 5⁴⁸. Female employment reflects the importance of female participation in economic life and the significance of gender equality in practice. Equal opportunities for both

Table 1 | Stakeholders, impact categories, and social indicators of the studied supply chain model

Stakeholder category	Impact categories	Social indicator	Definition of the social indicator	Unit of measurement	Direction of impact
Workers	Work safety	Occupational accidents in the supply chain	The occurrence arising out of, or in the course of, work which results in a fatal or non-fatal injury	Amount of fatal/non-fatal occupational accidents	Negative
	Gender equality	Female employment rates in the supply chain	The employment of female based on the divisions of labor between men and women	Employees as a percentage of female workforce	Positive
	Informal employment	Illegal employment in the supply chain	Working arrangements that are in practice or by law not subject to national labor legislation, income taxation, or entitlement to social protection or other employment guarantees	Employees as a percentage of total employment	Negative
	Labor share	Total labor income as a share of national Gross Domestic Product (GDP)	The total compensation of employees and the labor income as a percent of GDP	Total labor income as a percentage of GDP	Positive
Local communities	Employment	Employment rates in the supply chain	The extent to which available labor is being used	Employees as a percentage of workforce	Positive
	Child labor	Children engaged in supply chain processes	Number of children aged 5–17 years engaged in economic activities	Child workers as a percentage of child population	Negative

male and female in participating in economic activities demonstrate a strong base for gender equality. In this study, female employment rates are considered as the indicator assessing gender equality levels in the critical energy materials supply chain. Equation (3) refers to the mathematical formulation of the female employment ($F_{x,i,j}(t)$):

$$F_{x,i,j}(t) = \frac{f_{x,i,j}(t) \times r_{x,i,j}(t)}{Lf_j(t)} \times 100 \tag{3}$$

where $f_{x,i,j}(t)$ is the number of female employees required to produce one-tonne output at stage $x = 1, 2, 3$ (mining, processing and product manufacturing) of element $i = 1, 2, 3, \dots, 13$ (REEs, Ni, Si, graphite, Mg, Ga, Ge, In, Al, Co, Li, Zn, and Te) in country $j = 1, 2, 3, \dots, 33$ (Australia, Brazil, Burundi, China, India, Madagascar, Malaysia, Myanmar, Thailand, US, Vietnam, Indonesia, Philippines, Russia, Bosnia, Canada, France, South Africa, Iran, Hungary, Japan, Botswana, Democratic Republic of Congo (DRC), Mexico, New Caledonia, Papua New Guinea, Turkey, Zambia, Zimbabwe, Argentina, Chile, Bolivia, and Peru) in year t of the period 2010–2030; $r_{x,i,j}(t)$ is the mass flow (tonne) of output at stage x of element i , in country j ; and $Lf_j(t)$ is the female labor force variable. For the purpose of our study, the term ‘labor force’ means active individuals who fulfill the requirements and are able and willing to be employed⁴⁸.

Informal employment

Informal employment corresponds to any type of employment that is neither taxed nor monitored by government authorities. It leads to the absence of any environmental or health security for workers and the absence of any rule that would require mandatory certifications and licenses before starting the work⁴⁹. The eradication of informal employment is essential to promote the creation of decent jobs (8.3.1 SDG target) and to include the working groups in the social protection system (1.3.1 SDG target)¹⁸. Informal employment often leads to a lack of social protection for workers (i.e., inability to ensure decent living conditions for the whole population throughout their lives), including access to benefits such as health care, unemployment insurance, and retirement savings. This work assesses the number of employees working informally along the energy materials supply chain model. The mathematical formulation to measure the informal employment levels ($I_{x,i,j}(t)$) is presented by Eq. (4).

$$I_{x,i,j}(t) = \frac{i_{x,i,j}(t) \times e_{x,i,j}(t) \times r_{x,i,j}(t)}{T_j(t)} \times 100 \tag{4}$$

where $i_{x,i,j}(t)$ is the proportion of informal employment at stage $x = 1, 2, 3$ of element $i = 1, 2, 3, \dots, 13$ in country $j = 1, 2, 3, \dots, 33$ in year t of the period 2010–2030; $e_{x,i,j}(t)$ is the number of employees required to produce one tonne of output at stage x ; $r_{x,i,j}(t)$ is the mass flow (tonne) of output at stage x , of element i , in country j ; and $T_j(t)$ is the total employment.

Labor income share

The labor income share has always attracted little attention due to its stability (i.e., with minimum fluctuation over time). A low share of labor income might directly affect several areas, including the purchasing power, household consumption, exports, and government consumption⁵⁰. This social indicator addresses the economic contribution to the region’s GDP to achieve the 8.5 target of the SDG addressing decent work with equal pay¹⁸. This study considers the total labor income share via the critical energy materials supply chain as part of the GDP (Eq. (5)):

$$L_{x,i,j}(t) = \frac{K_{x,i,j}(t) \times e_{x,i,j}(t) \times r_{x,i,j}(t)}{GDP_j(t)} \times 100 \tag{5}$$

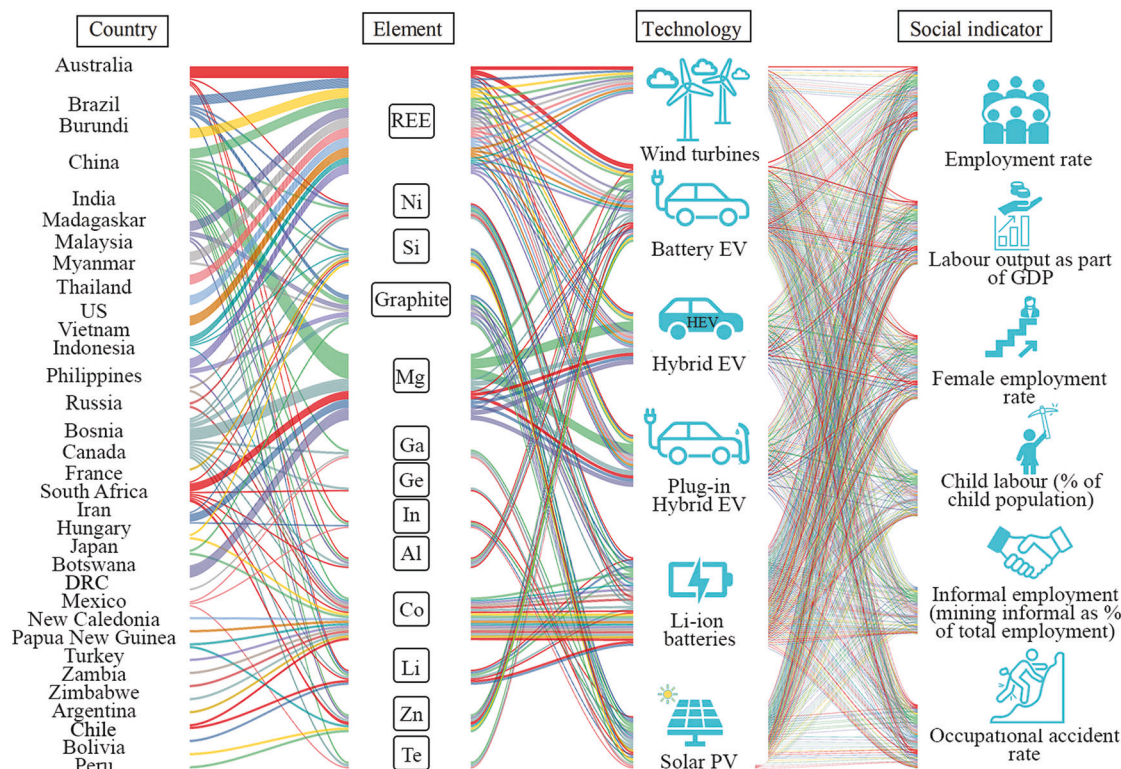


Fig. 5 | Network model design of the dynamic social assessment of energy technologies and the associated list of critical materials for green energy technologies. The diagram illustrates the flow of materials from extraction in top producer countries, through their use in technologies, and onward to their social

impacts. This comprehensive overview helps show how materials move through these systems and where they are concentrated to discover opportunities to manage materials sustainably.

where $K_{x,i,j}(t)$ is the annual salary earned per employee at stage $x=1, 2, 3$ of element $i=1, 2, 3, \dots, 13$ in country $j=1, 2, 3, \dots, 33$; $e_{x,i,j}(t)$ is the number of employees required to produce one tonne of output at stage x , of element i , in country j ; and $GDP_j(t)$ is the national gross domestic production in year t of the period 2010–2030.

Employment rate

Employment plays a significant role in strengthening social and economic autonomy as well as social well-being⁵¹. Its importance is highlighted as a powerful tool to achieve the SDG target 8.3 of promoting policies to support job creation and growth of enterprises. Communities are the primary target of enhancing local employment rates. In this work, employment refers to individuals within a working age group who are actively engaged in economic activities for pay or profit. The employment rates consider labor employment via the critical energy materials supply chain. The employment rate ($E_x(t)$) is calculated by Eq. (6).

$$E_{x,i,j}(t) = \frac{e_{x,i,j}(t) \times r_{x,i,j}(t)}{Lb_j(t)} \times 100 \quad (6)$$

where $e_x(t)$ is the number of employees required to produce one tonne of output at stage $x=1, 2, 3$ of element $i=1, 2, 3, \dots, 13$ in country $j=1, 2, 3, \dots, 33$ in year t of the period 2010–2030; $r_{x,i,j}(t)$ is the mass flow (tonne) of output at stage x , of element i , in country j ; and $Lb_j(t)$ is the workforce variable.

Child labor

Eradication of child labor has become a major target to promote a decent work environment⁵². Around 150 million children (aged <15) are

engaged in economic activities⁵³. Despite the decreasing trend of child labor in the past decade, the trend has slowed down¹⁸. This indicator addresses the 8.7.1 target among the list of SDGs for eradicating child labor¹⁸. This study considers the child labor issue along the energy materials supply chain processes. The number of children engaged in child labor ($C_x(t)$) is calculated according to Eq. (7).

$$C_{x,i,j}(t) = \frac{cw_{x,i,j}(t) \times r_{x,i,j}(t) \times e_{x,i,j}(t)}{Ch_j(t)} \times 100 \quad (7)$$

Where $cw_{x,i,j}(t)$ is the number of children engaged per one worker at stage $x=1, 2, 3$ of element $i=1, 2, 3, \dots, 13$ in country $j=1, 2, 3, \dots, 33$ in year t of the period 2010–2030; $e_x(t)$ is the number of employees required to produce one tonne of output at stage x of element i in country j ; $r_{x,i,j}(t)$ is the mass flow of materials at stage x , of element i , in country j ; and $Ch_j(t)$ is the child population variable.

Work safety

Minimizing occupational accidents in supply chain activities is a prominent factor in ensuring a healthy and safe working environment. It is one of the targets associated with SDG 8 designed to sustain economic growth, i.e., target 8.8.1 (putting an end to occupational injuries)⁵⁴. This work measures occupational accidents associated with the manufacturing stage, i.e., manufacturing of wind turbines, solar PV panels, batteries, and EVs. Equation (8) refers to the calculation needed to quantify occupational accidents, ($A_x(t)$).

$$A_l(t) = a_l(t) \times r_l(t) \quad (8)$$

Where $a_l(t)$ is the number of accidents occurring after producing one-tonne output $l=1, 2, 3, 4, 5, 6$ (wind turbines, solar PV panels, NiMH

and Li-ion batteries, battery EVs, plug-in EVs, and plug-in hybrid EVs) in year t of the period 2010–2030; and $r_i(t)$ is the amount flow (tonnes) of output $i = 1, 2, 3, 4, 5, 6$.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The authors declare that all data supporting the findings of this study can be found in the article and/or its Supplementary Information and Supplementary Data 1. Source data are provided with this paper.

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Author contributions

S.R., M.E.W., and A.K. designed the work. S.R., M.E.W., and I.M. collected the data. S.R., M.E.W., and I.M. created and validated the model. S.R., M.E.W. I.M., and A.K. carried out the data visualization. S.R., M.E.W., I.M., M.L., and A.K. wrote the original draft of the manuscript. S.R., M.E.W., H.L.T., M.L., and A.K. reviewed and edited the manuscript. A.K. supervised the work.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Saeed Rahimpour or Mohammad El-Wali.

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