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Editorial

Critical Raw Materials and Supply Chain Disruption in the Energy Transition

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The energy transition towards efficient energy production, transport, and use, renewable energy (RE) technologies and innovative energy management brings benefits to reducing greenhouse gas (GHG) emissions and achieving climate targets. The transition requires resources, minerals, metals, and materials for RE technologies themselves, for example, solar photovoltaics (PV), hydrogen fuel cell vehicles (HFCVs) as well as innovative supporting technologies for variable RE, for example, energy storage systems (ESSs). This requirement of resources and materials occurs over the whole supply chain of the technologies, from the extraction of resources, the manufacture of technology, and the deployment of technology, till the very end of its life cycle. In such context, the consideration of resources in general and critical raw materials (CRMs) in particular and their relations to the risk of supply chain disruption are highly important for achieving the global green energy transition. This editorial paper provides a brief view of the close connectivity between materials/resources and the green transition over the whole supply chain of energy technologies.

The editorial paper includes 11 papers covering the energy transition all over the globe. In these papers, the future national energy transition with a specific energy or climate targets is predicted by applying the energy model [1–3] and relevant energy, materials, and resources required for energy production can be estimated [2,3]. At the global level, [4] study the relations between fossil and renewable resources for energy transition, taking into account the energy security and regional trade. Some authors extend to 'soft' measures for low carbon energy transition such as the energy prosumer business model [5] or the sector coupling of water and energy supply [6,7]. Apart from environmental benefits, the economic, social, and sustainable consequences of RE technologies and energy transition are quantified and assessed [8–10]. A list of CRMs for energy transition and their availability index is presented in [11].

Limpens et al. [1] use the EnergyScope Typical Days model to analyze the Belgian energy system in 2035 for different carbon emission targets. It is a regional, bottom-up and linear model considering multiple sectors and multiple energy carriers with an hourly resolution and a 1-to-5 min computational time. This model optimizes the design and operation strategies of the system including a set of 96 energy technologies, from 24 resources while meeting the end-use demand of electricity (TWh), heat (TWh), mobility (passenger km and tonne km) and non-energy demand (TWh), and minimizing the total annual cost of the system. Besides, the optimization of the system was constrained under a climate target limiting its annual life cycle GHG emissions. It is identified that by 2035, Belgium will lack 275.6 TWh/year of local resources, and 173.3 TWh/year if non-energy demand is not taken into account. To pursue the cost-effective, green energy transition, the demand gap could not be met by individual renewable energy technologies such as offshore wind, geothermal or nuclear power, consequently requiring a mix of renewable solutions. At the same time, the imported renewable fuels or electricity is not a cost-competitive solution (assuming that the price of imported renewable fuels is 50% higher than that of the fossil ones), except for aiming at very low emissions. [1]

Rixhon et al. [2] conducted an uncertainty analysis with a whole-energy system model to study the importance of electro-fuels such as hydrogen, methane, and methanol in Belgium's energy transition by 2050. The applied whole-energy system model was EnergyScope Typical Days, which is the same as that of [1]. Only two differences are made, including the timeframe of the study, and the negligence of non-energy end-use demand. In the model, Belgium was modeled as a single node without taking into account intra-national energy transmission. For the uncertainty analysis, the polynomial chaos expansion method was used to highlight the influence of the critical parameters of energy/fuel price, transportation technology costs, technological efficiency, and nuclear power capacity on the total cost of the system.

Under the uncertainties, the annual system cost of 43.6 billion Euros by 2050 could become 17% higher and twice more uncertain in the context of the zero-emission target. Specifically, the price of imported renewable electrofuels is the most critical parameter, contributing to 53.2% of the variation in the total cost of the system. The price of fossil hydrocarbons significantly impacts the variation of the system cost, at 34.8%. The maximum capacity of nuclear power plants has a limited impact of 13.1% on the variation of the total annual cost of the system. Lastly, two transportation-related parameters of the investment cost of cars and of fuel cells have a small impact on the variation of the system cost. The limitation of this uncertainty analysis study lied in the independency of parameters. Though the independency of the parameter is required by the polynomial chaos expansion method, it does not reflect the reality of technology modeling in some cases, for example, the close relation of the technology's investment cost and its efficiency. The authors suggested future studies on the application of electrofuels/biofuels and the characterization such as price, availability, geographical origin, production process, etc of imported electrofuels/biofuels to make the model more refined, realistic and comprehensive. [2]

Delannoy et al. [3] combine GlobalShift and a dynamic function to model the Energy Return On Investment (EROI) of natural gas at a global scale by 2050. GlobalShift composes of data on gas reserves and production for the period of 1950–2050 by gas-producing countries, which is used to quantify energy production. The dynamic function is then applied to analyze the uncertainty of EROI. It is found that 2040 will see the gross energy peak of 249 EJ, while the net energy will reach a peak at 210 EJ in 2037. The average EROI steadily decrease from 141.5 to 16.8 between 1950 and 2050. The energy required to produce gas is 11 EJ, corresponding to 6.7% of gross energy produced in 2020. By 2050, this number will mount up to 53 EJ, or 23.7% of gross energy production. With the exponential increase in the required energy for gas production or the sharp decrease in its EROI, there is a risk to energy security as well as the environment, which suggests the inclusion of EROI in energy transition studies [3].

Berdysheva and Ikonnikova [4] propose a modified index for energy security, and apply it to the global energy trade to understand the growth in the unconventional resources in the United State of America, RE in Europe (EU), Chinese natural gas consumption, and changes in other countries' energy flows, as well as their relations to the energy transition, the economic situation and the trade network. The authors use a six-step approach of (1) update data on energy production, consumption, and trade 2000–2008, (2) compare data of the International Energy Agency and United Nations' commodity trade to see the energy flows, and (3) compile data for monetary flows to see the economic link, (4) characterize individual -economy energy systems' evolution, in relation to trade, (5) apply complex network method to see the evolution of trade and test the small world property to see the change in the cluster and network of energy over time, and (6) use modified energy security index to see the change in demand, supply, and trade. The results show that the green energy transition toward higher investment in RE does not improve energy security in most countries (even make it worse). The reduction in coal consumption changes the fuel diversification balance and weakens energy security. The increased reliance on natural gas causes a negative impact on energy security; but expanding the liquified natural gas trade reduces the negative impact. The growth in global energy demand induces major energy exporters to produce more, exposing them to supply risk.

The business model of tenant electricity, which provides tenants of a building with on-site solar power, offers the potential to achieve energy transition and GHG reduction targets. In Germany, Moser et al. [5] study barriers to and drivers of diffusion of the tenant electricity, using qualitative data analysis and semi-structure expert interviews. The identified main barriers are the legal framework which causes high transaction costs, and the reluctancy of residents to become prosumers of electricity. Meanwhile, the drivers of this business model include increasing electricity demand, technical development such as blockchain and smart meters, and EU RE directives [5].

Torabi et al. [6] study the penetration level of electric vehicles (EVs), and sector coupling (of water supply and energy management) in an island of Portugal to highlight the contribution of optimized management of RE resources on its energy transition. The island's energy system is transitioning towards the dominance of solar and wind energies. With the high share of RE, curtailment is inevitable. To support this transition and minimize the curtailment, three solutions have been identified, including the deployment of ESSs, EVs, and demand side management of water desalination plants. These solutions are evaluated by optimizing the system while maintaining the power supply being equal to the demand plus curtailed power. It was identified that the share of RE may reach 100% and the curtailment events could be reduced by the large-scale deployment of EVs and demand management of desalination plants and charging management of ESSs and EVs. At the same time, the greenhouse gas emissions of the mixed grid reduce accordingly [6].

Zohrabian and Sanders [7] estimate the energy and GHG emission trade-offs of projected water supply in Los Angeles by 2050. The electricity demand for surface water supply and recycled water system between 2010 and 2050 is calculated by applying an energy intensity for annual water volume from different sources. The factors impacting electric demand for water supply are then decomposed to highlight their importance. The corresponding GHG emissions are quantified with the current emission intensity of the current and future grid mix. The results show that treating stormwater and recycling water bring benefits for coping with water shortage; however, these measures might not considerably benefit in terms of electricity demand. Water conservation brings benefits of energy savings which are higher in the case of using locally supplied water than imported water. At the same time, increasing the local water sources in replacement of imported water will cause the geospatial change in energy demand from outside the city (for recycling water) to inside the city (for pumping local water). As a result, the local electricity system and its corresponding GHG emissions will be impacted. The decomposition analysis indicates that the change in the local water supply structure has a higher impact on the electricity demand than population growth and water conservation [7].

Bethoux [8] studied the barriers to expanding the deployment of Hydrogen Fuel Cell Vehicles, HFCVs, on the mass road transportation vehicle market, considering the environmental and economic aspects over the whole supply chain of production, storage, and distribution of hydrogen. It is identified that there is a market for using hydrogen for both light and heavy road transportation. Green hydrogen may be one of the potential uses of renewable energies and natural hydrogen might become an economic reality pushing the HFCVs to be a competitive and environmentally friendly alternative to battery electric vehicles. In the meantime, some barriers that need to be overcome, so as to reduce the vehicle and fuel technologies' cost, increase vehicle durability, the lower environmental footprint of the vehicle, especially in the manufacturing and disposal stages, improve hydrogen production technologies, enhance the safety of the hydrogen infrastructure as well as the vehicle [8].

Pietrzak et al. [9] conducted a critical situation assessment of RE sources in Poland, taking into account three aspects of physical energy sources, energy policy, and social awareness. Through a semi-structured expert-assessment survey, the study points out that Poland has large RE resources, and there is a potential for further exploiting this resource in the near future. Specifically, the potentials for solar, wind, and solid biomass development are assessed to be the highest among different RE technologies. Some factors preventing the deployment of RE have been identified, including the conventional energy lobby, complex RE regulation, and high investment costs. In order to achieve the energy transition, five activities such as change of the national law, public education on RE, financial incentive and tax exemption for RE investment, development of prosumer energy, and dialogue with the coal lobby are suggested by the experts [9].

Hale and Long [10] evaluate sustainability outcomes of energy transition using univariate time series prediction model. The authors use exponential smoothing and AutoRegressive Integrated Moving Average (ARIMA) model to predict the annual electricity generation supply by 2029. The predicted electricity generation with the lowest uncertainty, obtained with the ARIMA model is assessed for four sustainability indices of carbon, water, land, and cost footprints. The change in electricity generation structure (reduction in coal and increase in solar and wind) and the increase in electricity generation during 2020–2029 will cause an increase in land and cost footprints, but a decrease in carbon and water footprints. In case the increase in coal-based electricity is substituted by solar only, the land footprint increases by the smallest rate, and but the cost is the largest among different substitution strategies. Meanwhile, the substitution with wind is the best strategy in terms of water and cost footprint, but the worst one in terms of land footprint [10].

Nate et al. [11] provide an availability scoring of 17 critical materials concerning 10 energy technologies. The availability of these critical materials is ranked by their current, absolute amount used for energy technologies, their projected, percentage annual demand by 2050 compared to the current value, the number of technologies requiring these critical materials, their accumulative emissions of CO2, their reserves availability, the number of countries producing more than 1% of global production and the countries with highest annual material productivity. Two supply-demand scenarios have been developed using independent parameter probability and supply-demand balanced fuzzy estimation. It is identified that cobalt, graphite, and lithium, which are used for ESSs, have the lowest material availability ranking index. These materials are followed by iron, nickel, and chromium. With the changes in the supply-demand balance, cobalt, lithium, rare earth elements, iron and vanadium are the most unpredictable materials [11].

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