Closing the TIMES Integrated Assessment Model (TIAM-FR) Raw Materials Gap with Life Cycle Inventories

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Summary

Energy system models ignore raw materials cycles and in-use material stocks. In this paper, we introduce a material accounting method as a first step towards addressing the raw materials gap in the TIMES Integrated Assessment Model (TIAM-FR version). The method consists in attributing life-cycle inventories (LCIs) taken from the Ecoinvent 3.3 database to the TIAM-FR technology processes constituting the world energy system. We start by disaggregating the LCIs into three separate life phases (construction, operation, and dismantling) and coupling them to their respective TIAM-FR process outputs (new capacities, operation, and retiring capacities) in order to estimate the annual raw materials requirements. We then demonstrate the method on the electricity generation sector in a baseline scenario on the 2010-2100 horizon. Prospective uses of fossil fuels and metallic and non-metallic mineral materials are quantified dynamically at the life phase level. The construction and dismantling of hydropower, solar and wind capacities generate increasing amounts of metallic and non-metallic raw materials in successive peak and valley periods. However, the total use of raw materials is largely driven by fossil fuels all along the horizon. Finally, we evaluate the sensitivity of global material use to variations in the technologies' dismantling phase. This novel approach can be extended to other energy system models and possibly other energy sectors.

Keywords

Raw materials ; Energy system model ; Prospective scenario ; TIMES ; TIAM-FR ; Ecoinvent ; Life-cycle inventories ; Integrated assessment model; Material flow analysis

Introduction

Following the recent development of large-scale energy system models (ESMs), it is possible to investigate the complexity of energy systems and their multiscale evolution. Among the variety of existing models, world models stands out due to their wide scope, comprehensive overview and closed-loop nature. The most authoritative projections such as the IEA's World Energy Outlook [1], the EIA's International Energy Outlook [2] and the WEC's World Energy Scenarios [3] provide world energy system scenarios constrained by physical, technological, and economic drivers, as well as environmental policies. These models result from bottom-up, top-down or hybrid descriptions of the energy system following optimized or simulated development trajectories that satisfy a set of constraints. Although these have become increasingly integrated and detailed using large quantities of data, they ignore mineral raw materials stocks, flows, transformations, functions and services.

World energy scenarios usually assume rising demand. This results in the development of supply chains, which require increasing primary energy and raw materials. In 2015, about 81% of global energy production came from fossil fuels. More than a quarter of the world's primary energy supply (3.6 Gtoe) was directed to electricity and combined heat-and-power (CHP) plants as fossil fuel products [4], as shown by (Figure 3). This share increased steadily for decades (hatched area) until it stabilized recently.

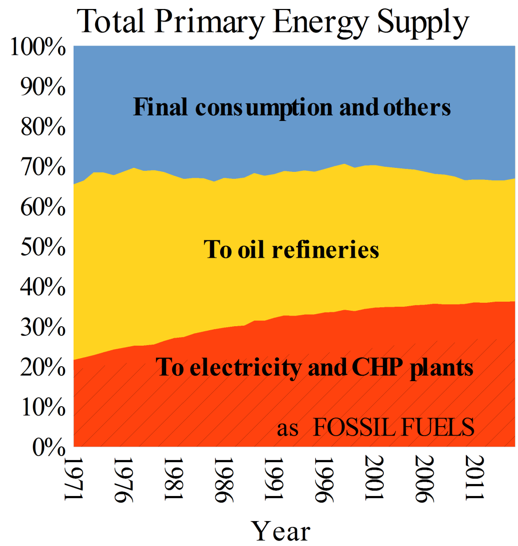

Figure 1: Distribution of total primary energy supply (TPES) to main energy sectors. 2015 TPES (IEA): 13.6 Gtoe

In the context of sustainable development, removing fossil fuels from energy processes is a challenge. Multiple prospective studies deduce that more raw materials — especially metals — could be required in the coming decades following the development of low-carbon and energy-efficient technologies [5–14]. Available material reserves and processing capabilities might not be sufficient to cover future material needs, driven by economic growth. This perspective leads to two reciprocal questions: 1) What are the implications of long-term prospective scenarios for raw materials? and 2) What are the impacts of raw materials on long-term prospective scenarios? Determining the answer to the first question would bring valuable knowledge about raw materials in potential high demand in the future , and it could be used to achieve more efficient resource management and more resilient material supply chains, thus mitigating material criticality. Addressing the second question would provide elements to determine whether or not raw materials cycles should be considered in a given scenario. For instance, when raw materials have a significant influence, this could mean that the scenario is not relevant and that it needs to be re-assessed taking into account this new information. Ideally, the two questions above are addressed together using a systems approach. From this perspective, a study of the mutual interaction between raw materials and energy scenarios is relevant and may be tackled using different industrial ecology tools like material flow analysis (MFA) and life-cycle assessment (LCA). In this direction, Hertwich et al. performed a prospective integrated life-cycle assessment of the electricity generation sector to 2050, based on IEA's 2015 Energy Technology Perspective report [15]. Their work revealed that LCA metrics carry crucial information that needs to be considered by both energy system modelers and policymakers. Life cycle metrics are still rarely considered in integrated assessment models [16,17]. In this paper, we make a first step towards integrating raw materials into the TIMES integrated assessment model (TIAM). TIAM is a bottom-up world energy model that was developed by the Energy Technology Systems Analysis Program (ETSAP) group of the IEA [18]. It provides decision-makers with prospective multiregional energy scenarios. The detailed description at the technology level in TIAM allows us to use life-cycle inventories (LCIs) in order to access the life-cycle material use of each technology. From there, we introduce a novel life-cycle material accounting method that is used to address question 1 above. First, we describe the method that attributes LCIs to the TIAM-FR processes. In particular, the technologies' LCIs are disaggregated into three phases: construction, operation and dismantling, in order to dynamically monitor each technology's use of raw materials. Second, we determine a baseline scenario in the French version of TIAM (TIAM-FR). Third, the method is applied to the electricity-generating technologies in the baseline scenario, with an estimation of their fossil fuel and metallic and non-metallic mineral raw materials requirements on the 2010-2100 horizon. Fourth, the sensitivity of the total material use to a larger or smaller dismantling phase is investigated. Finally, we provide perspectives relating to the full integration of life-cycle inventories in TIAM-FR.

Method

The TIAM-FR model

TIAM is a bottom-up model in the TIMES family. TIAM-FR is the French version of TIAM with additional power technologies (carbon capture and sequestration) and biomass commodities. It depicts the world energy system with a high level of details on energy sources, technologies, and end uses. A Reference Energy System (RES) connects commodities to current and future technologies in different energy use sectors (upstream, agriculture, industry, commercial, residential and transport). The RES includes the collection, transformation, distribution, trade and end-use of main energy carriers including fossil fuels, biomass and uranium. These material commodities have limited stocks (or potentials) and are converted into energy equivalent quantities so that they can be monitored and processed on a common account. Steel, iron, pulp, and non-ferrous metals are also considered but only as exogenous demand drivers for their respective industries. Other mineral raw material commodities are ignored. In each of the 15 world regions represented (Africa, Australia and New Zealand, Canada, China, Central and South America, Eastern Europe, Former Soviet Union, India, Japan, Middle East, Mexico, Other Developing Asian countries, South Korea, United States of America, Western Europe), TIAM-FR establishes a balance between supply technologies and a set of demand drivers including gross domestic product growth, population growth, electricity demand, and others [19]. The model computes the total net present value of the total annual cost, discounted at 5% from the selected reference year 2010, and optimizes the technological field until a least-cost solution is found. Perfect competition and full foresight are assumed. The optimization is performed on 11 periods the lengths of which are given in Table 1.

The method is demonstrated on the electricity generation sector only, although the full model is used. The different 215 electricity generating processes that constitute the electricity generation landscape are grouped into the following 10 categories : BIO: biomass, COA: coal, GEO: geothermal energy, HYD: hydropower; OIL: oil, NGA: natural gas, NUC: nuclear energy, SEA: tidal, SOL: solar photovoltaics and concentrating solar power, and WIN: wind. CHP plants are included (excluding heat production) whereas electric storage and distribution technologies are excluded. Individual technologies and process classification can be found in the supplementary material (supp. mat. Table 1). Three electricity-related outputs are used: the newly-installed electric capacities in GW, the electric production in PWh, and the retiring capacities in GW. These quantities are annualized on each period by dividing by the period length (see Table 1).

Period #	1	2	3	4	5	6	7	8	9	10	11
Period mid-year	2010	2013	2020	2030	2040	2050	2060	2070	2080	2090	2100
Period length (yr)	1	5	9	11	9	11	9	11	9	11	9

Table 1. Period lengths in the TIAM-FR model

Life-cycle inventories

The Ecoinvent 3.3 database is currently one of the largest public life-cycle inventory databases [20]. In Ecoinvent, available processes, activities, products and technologies are built from elementary LCI processes. This structure makes it a consistent framework for life-cycle assessments (LCA) and product comparisons. Once all processes involved in an activity have been identified, several calculation methods are available depending on how these are linked and form a system [21]. Allocation methods are usually opposed to consequential approaches. Allocation methods account for process inputs and outputs and attribute them to a share of the process's functional unit. Consequential approaches aim at integrating the changes around a process following its development assuming small-scale changes and long-term horizon. This approach accounts for additional or fewer relative inputs and outputs following the implementation of a process or technology. The consequential approach creates an incentive for technologies that are likely to reduce not only their impacts but also the impacts of their environment (e.g. low-carbon technologies reduce the carbon footprint of other technologies). This is why this is the preferred approach in prospective impact assessments and decision-making, though no agreement exists on whether to use one or the other in general cases [22–25]. Even though a consequential method is proposed in Ecoinvent, we opt for an allocation method for three main reasons: 1) Consequential methods typically require more data and are more uncertain than allocation ones due to the larger system encompassed and the policies assumed. 2) The assumptions made in the Ecoinvent consequential system model are not disclosed [initiatives are underway to allow for custom open-source system models [26]]. Thus, consistency with theTIAM-FR scenario is not guaranteed. 3) [27]'s analysis states that "[allocation methods are] appropriate when comparing various power generation technologies with each other on a life-cycle basis in the absence of any policy decision that may favor one technology over another", which is in agreement with our approach. The

default *at the point of substitution* allocation method is selected. In this specific method, LCI processes share the burden of recycled/reused byproducts between primary and secondary process activities.
A variety of electricity producing technologies are documented in Ecoinvent, but some are missing (concentrating solar power) or incomplete (nuclear, hydropower). As not every TIAM-FR technology process has a corresponding LCI in Ecoinvent, all processes in a similar technological family (as defined in the previous section) are attributed with the same LCI. Other databases and literature that could complement missing data or provide more "balanced" estimates are intentionally avoided for consistency, transparency and reproducibility purposes. An exception is made for concentrating solar power for which an unofficial dataset is used [28]). Regular updates, verified data and a large number of users make the Ecoinvent database suitable for comparing datasets, filling data gaps and spotting unrealistic assumptions [29].

Coupling LCIs with TIAM-FR outputs

Life-cycle inventories list all substances according to the functional units of the technology processes, expressed in unit kg kWh^{-1}. This format is ideal for rating technologies that have short lifetimes and invariable life phases ; however, it is not convenient for analyzing long lifetime technologies with high variability in their construction, operation, and dismantling phases. Furthermore, a single mass-per-electric-output figure is not suitable to represent the life-cycle material requirements of technologies that do not have a steady electric output but rather operate intermittently or as back-up generators. For these technologies, a minimum of 3 phases — construction, operation, and dismantling — seems reasonable to capture their life-cycle material uses. A necessary feature of this phase separation is the introduction of the functional unit kg GW–1 for the construction and dismantling phases where instead of electricity, a capacity is produced (or removed). Ecoinvent makes accessible a list of the activities involved in the technology's life cycle. However, the life phase in which each activity occur is not documented. We separate the life phases into two steps: first, the infrastructure activities are identified and deducted from other operation activities. When such identification is not possible (e.g. for biomass), the whole activity LCI is counted as the operation phase, and the construction and dismantling are assumed to be burden-free. Second, the available infrastructure activities are distributed between the construction and dismantling phases. However, due to a lack of data, a ratio α is introduced that sets the percentage of the infrastructure LCI that is attributed to the dismantling phase, while the complementary part, 1-α, is attributed to the construction phase. The rationale of this bold assumption is that it allows us to evaluate the sensitivity of the technologies' material use to non-zero dismantling phases while maintaining consistency and mass balance with the original infrastructure LCIs.

The available infrastructure LCIs (construction + dismantling phases) are first expressed in kg of materials to produce one power plant. Then, these are divided by their corresponding power capacity to yield kt GW–1 figures. The service lifetimes of the technologies are assumed to be equivalent in Ecoinvent and TIAM-FR. The transformation LCIs (operation phase) are shown in the unit kg W–1 h–1 and are simply converted into kt PW–1 h–1 (or kt per PWh). Figure 2 shows the schematic disaggregation method and coupling with the TIAM-FR outputs. The construction LCI is attached to the new capacities, the operation LCI is attached to the electric production, and the dismantling LCI is attached to the retiring (or end-of-life) capacities. Installed capacities may produce electricity intermittently or not at all, depending on the model constraints. In order to avoid potential misleading results at the regional scale, the dynamic material bill of each technology is displayed annually after summation over all world regions. The Ecoinvent datasets and their attribution to the TIAM-FR technology processes are detailed in the supplementary material (supp. mat.Table 2).

Figure 2. Disaggregation method and coupling of technologies' LCIs to the TIAM-FR outputs

Raw materials

Each LCI comprises a list of materials that are involved in the technology's life chain within selected boundaries. Materials are either "substances" (solids, liquids, gases) or LCA-pertinent indicators such as land occupation, transformation and heat emissions. We choose to restrict the scope of this study to fossil fuel and metallic and non-metallic mineral raw materials as these appear in the LCIs. A list of substances and their classification can be found in the supplementary material (Table 3).

Results

TIAM-FR scenario

Figure 3 shows the TIAM-FR scenario outputs obtained in the studied scenario. The reference year 2010 being fixed, no capacities are installed or retired for that year. However, the electric production is known and grows from 21 PWh in 2010 to 45 PWh in 2050, and 61 PWh in 2100. Gas and coal capacities are increasingly installed until 2050 then stabilize at 50–100 GW per year. Solar energy capacity installations increase rapidly from 2020 and reach a global average installation rate of 90 GW per year in the second half of the century. The wind sector grows faster than solar over the 2010-2040 period but this trend reverses in 2040. Nuclear capacity investments are made over the 2010-2020 period in order to replace end-of-life capacities in Europe, Russia and Japan. After 2050, additional nuclear capacities are maintained at about 5-20 GW annually. Coal is the major electricity producer with almost half of the electricity production all along the scenario, followed by oil, natural gas, nuclear and hydropower. Solar and wind become significant electricity producers from 2040. Other sources of electricity production like oil (OIL), marine (SEA), biomass (BIO) and geothermal (GEO) power together contribute to less than 10% of the mix. End-of-life capacities come mostly from coal, gas and nuclear power plants which account for the largest share of the energy mix until 2040 when an increasing number of wind farms enter their end-of-life phase and are dismantled, as well as solar capacities from 2070. Periods with increased end-of-life capacities are generally compensated by new capacities to support electricity production. Geothermal power grows from 2090.

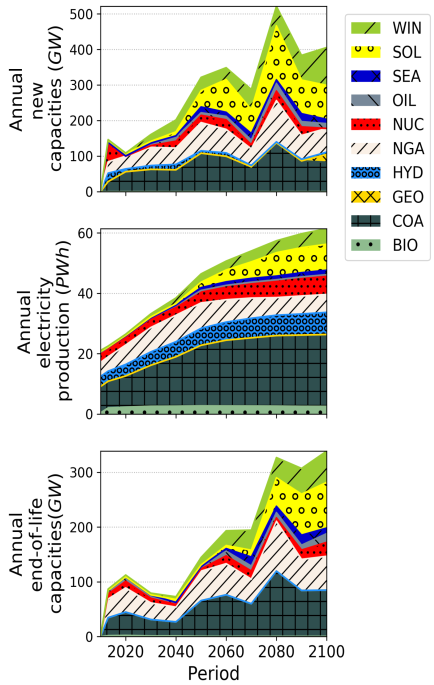

Figure 3. Annual new capacities (NCAP), electricity production (PROD) and end-of-life capacities (RCAP). The global electricity mix is represented by 10 technology categories (BIO: biomass, COA: coal, GEO: geothermal, HYD: hydro; OIL: oil, NGA: natural gas, NUC: nuclear, SEA: marine, SOL: solar, WIN: wind)

Raw materials use

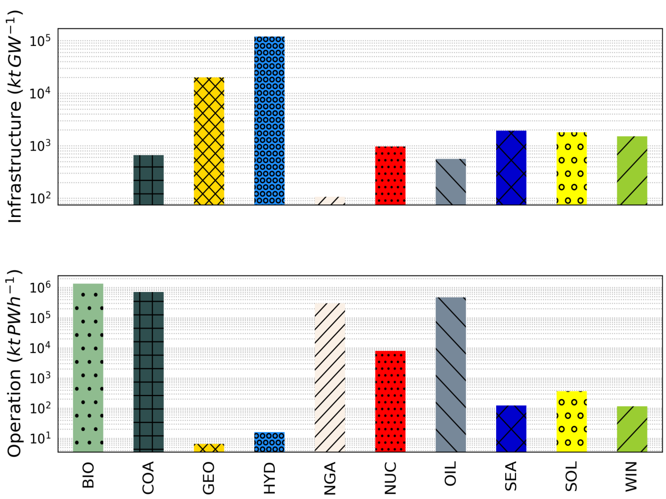

Figure 4. Materials requirements in the infrastructure (construction + dismantling) and operation phases of main electricity generation technologies (BIO: biomass, COA: coal, GEO: geothermal, HYD: hydro; OIL: oil, NGA: natural gas, NUC: nuclear, SEA: marine, SOL: solar, WIN: wind). The values are averaged on regions and periods

infrastructure and operation phases. However, the LCI used do not account for the construction of cooling towers and management and treatment of contaminated wastes, which could add significant material use.

By coupling the LCIs to the TIAM-FR scenario outputs, we obtain the annual life-cycle material requirements for each technology and material type. The results are calculated at $\alpha = 0.1$, meaning 10% of the infrastructure LCIs are attributed to the dismantling phase while 90% go to the construction phase.

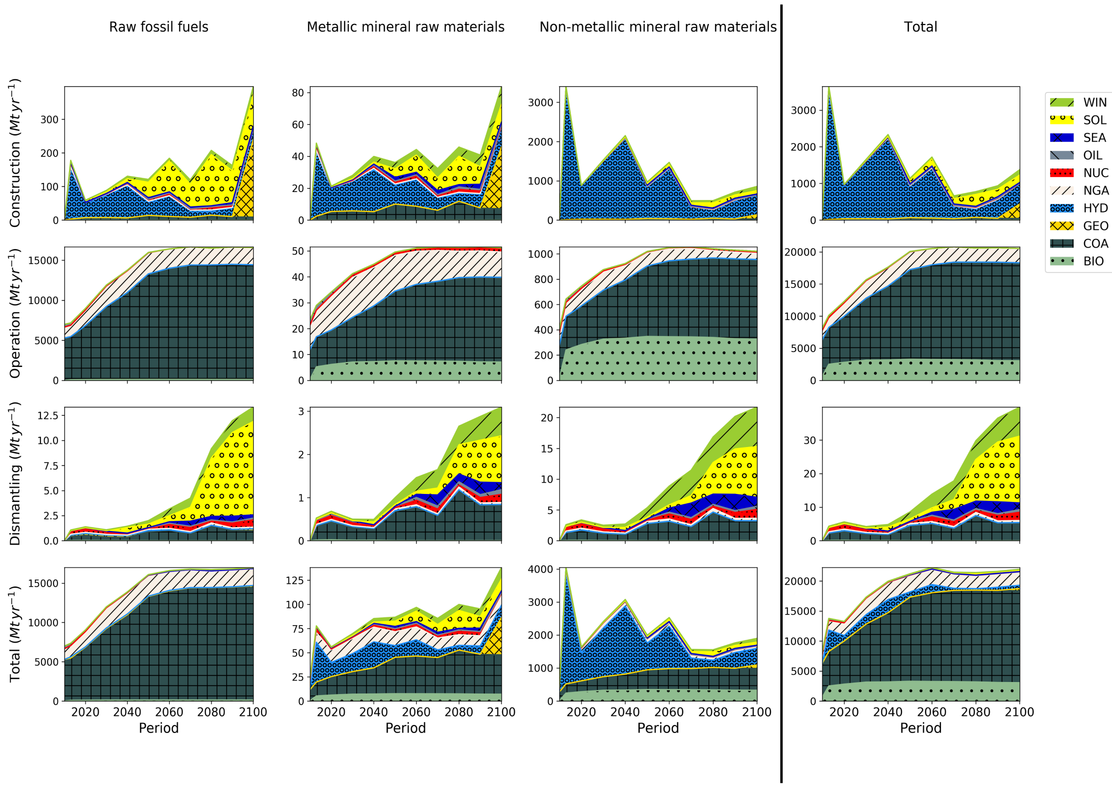

Figure 5. Total annual mass of fossil fuels, metallic, and non-metallic mineral raw materials needed in the construction, operation, and dismantling phases, $\alpha = 0.1$

Figure 5 shows the life-cycle use of fossil fuels, metallic materials and non-metallic mineral materials generated by the developing electricity-generating technologies. In the construction phase, fossil fuels are mostly used by hydropower. From 2040, the extensive development of solar energy requires an annual consumption of 50–150 Mt of fossil fuels per year. At the end of horizon, the fast development of geothermal facilities requires the largest amount of fossil fuels. Looking at material use in the dismantling phase, about 1–1.5 Mt yr of raw fossil fuels are used in coal, natural gas, and nuclear capacity dismantling. After 2030, dismantling of solar capacities is responsible for the largest share of fossil fuel use in this phase. These quantities remain low compared to the life-cycle amount of fossil fuels burned for coal and natural gas power plants during operation. Annual consumption peaks in 2060 at 17 Gt per year. If coal and natural gas mass amounts are converted into an oil-equivalent mass (assuming factors of 1.5 to 3 kt ktoe–1 for coal and 0.89 kt ktoe–1 for natural gas), the 2015 estimate of fossil fuel consumption by electricity and CHP plants (7.5 Gt) ranges from 4.0 Gtoe to 5.9 Gtoe. This is 11% to 64% higher than the actual value (3.6 Gtoe) featuring in the IEA's Key World Energy Statistics [4]. However, IEA statistics do not include the life-cycle effects associated with each sector, which partly explains the difference observed.

The use of metals in the construction phase follows a similar evolution to fossil fuels, except for relatively larger amounts of metals in coal and wind capacities, and smaller amounts in solar capacities. Metal use due to dismantling is dominated by coal capacities. Solar and wind end-of-life capacities generate a substantial use of metals in the second half of the horizon. Consumption of metallic materials is mostly due to fossil fuel and biomass power plants during the operation phase. The graph of the total use of metallic mineral raw materials shows that all technologies participate in the consumption of metals. Together, they could generate annual requirements of 80–90 Mt by 2050. For comparison, the 2015 world primary production of pig iron is estimated by the US Geological Survey at 1160 Mt. Coal and natural gas power plants are responsible for the largest share of the total use of metals.

Most of the non-metallic mineral raw materials used are attributable to new hydropower infrastructures for which outstanding materials use is assumed in the Ecoinvent LCI. In-operation material consumption is also substantial due to coal, gas, and biomass power generation. In the second half of the horizon, dismantling activities in solar, wind, coal, marine and nuclear plants generate most of the non-metallic raw materials use. The total use of non-metallic materials tends to decrease along the horizon with several surges in 2040 and 2060 resulting from the construction of large hydropower plants (reservoirs). Coal and biomass technologies represent the second and third highest consumption of non-metals. The material use generated by the dismantling activities ranges from 1% to 3% of the material use observed in construction phases (at $\alpha = 0.1$).

The totals plot shows that much greater amounts of raw materials are used in low-carbon technology infrastructures (especially hydropower) than in fossil fuel power plant infrastructures. However, the amount of fossil fuels including coal, natural gas and biomass burned in the operation phase by far exceeds all other material uses.

Sensitivity to the dismantling phase

When α varies, the material consumption dynamics are modified. Figure 6 shows the total annual uses of fossil fuels and metallic and non-metallic mineral materials for three values of α: $\alpha = 0.1$, $\alpha = 0.5$, and $\alpha = 0.9$. As expected, fossil fuel consumption is not significantly affected by α as most of the fossil fuels are used during the operation phase. When α increases, material use decreases. The raw mineral materials that were assumed in the construction phase of hydropower are partly shifted to the dismantling phase (which occurs after 2100). The differences between the raw materials requirements at $\alpha = 0.1$ and $\alpha = 0.5$ in 2050 are 0.3% for fossil fuels, 13.9% for metals, and 20.5% for non-metals.

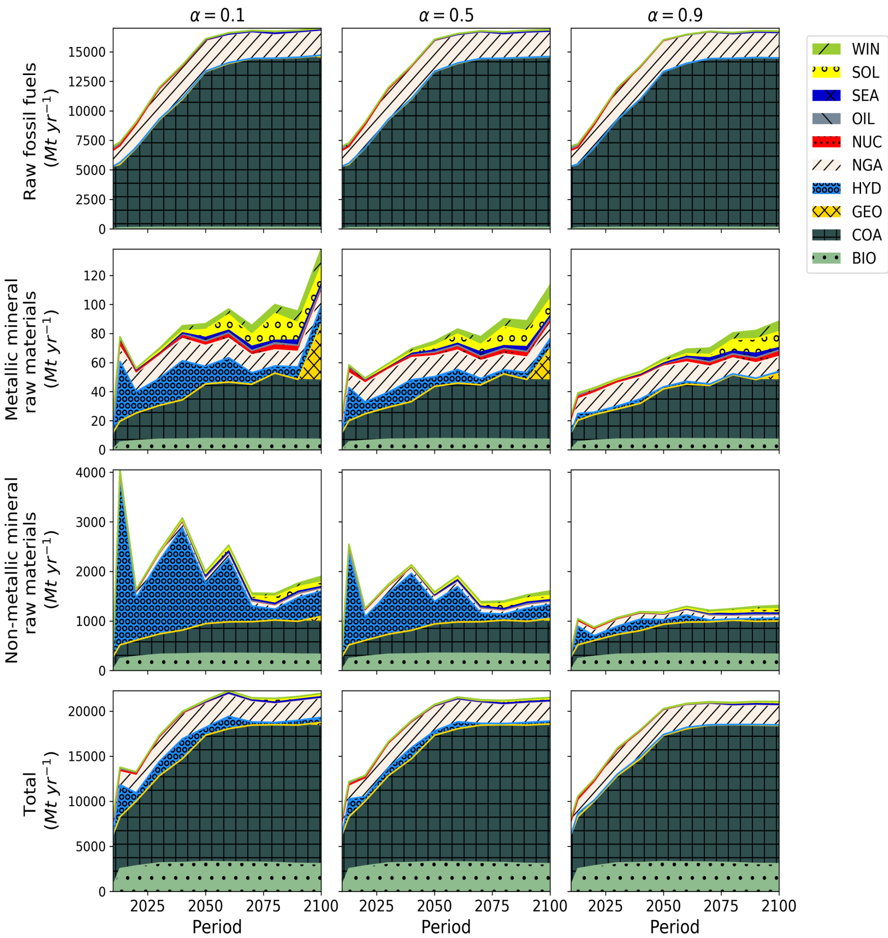

Figure 6. Total annual mass of fossil fuels, metallic and non-metallic raw mineral materials used by power generating technologies at α = 0.1, α = 0.5, and α = 0.9

Discussion

The TIAM-FR model — like most ESMs — does not consider variations in the in-use stocks of materials constituting the products and infrastructures. This results in subconstrained prospective scenarios that assume unlimited nonfuel raw materials resources. Yet, the long-term availability of several raw materials is not guaranteed in the context of economic development. Accounting for raw materials within the TIAM-FR model would require excessive amounts of data, which would have to be obtained from the material flow analysis of each substance and each technology process modeled. However, the model could allow such an implementation due to its high flexibility. Our approach is to keep the advantage of the model's high level of detail and use life-cycle inventories to estimate the future raw materials requirements of the world energy system as modeled in TIAM-FR. The disaggregation of LCIs into separate life phases makes it possible to represent the dynamic material use of the electricity-generating technologies during their construction, operation and dismantling phases. Another specific feature of our approach is that all substances listed in the life-cycle inventories are analyzed so that the total mass of raw materials used can be calculated. LCI is among the most effective tools to compare different technologies or products based on their life-cycle material use or content. However, datasets often come from different sources, use different data, at different times, and assume different system boundaries. We chose to rely on the Ecoinvent database solely to mitigate inconsistencies with other sources. In this study, several issues and limitations were identified. First, the LCIs are constant and do not interact with the scenario. Using invariable allocation LCIs may create large deviations when the external environment changes drastically during the technologies' life cycle periods, which may range from 15 years to more than 100 years. To partially address this issue, LCIs can be adjusted according to the electricity technology mix in order to reflect a more-or-less material-intensive power generation [30]. However, hybrid or consequential LCIs that are tied to a specific scenario are not relevant in other scenarios. Thus, consequential LCAs need to be improved to make more room for scenario customization [27,31], while keeping some representative invariants. Second, information loss between LCI providers and interpreters should be minimized in order to avoid biased results and interpretations. As an example, the LCI that is used for the hydropower reservoir technology infrastructure is documented as an average LCI across several technologies, but the power capacity is not explicitly provided. Third, most LCIs are shown in an aggregated form, with a single functional unit. This is not suitable to represent the material use of large infrastructures that may use large amounts of materials in a relatively short time. Other methods should be investigated that enable life-phase segmentation with multiple functional units. A recommendation for future LCIs would be to keep track of activities' timelines and the life phase in which each activity happens. Fourth, dismantling activities are unclear in the LCIs. During dismantling, the resources used may range from product destruction to land reclamation. Resulting waste materials may be landfilled, recycled or reused in other processes. Environmental impacts of dismantling thus result from negative burdens coming from the original product, mixed impacts due to destruction/disposal/recycling processes, and positive effects of avoiding additional primary material processing. These antagonist impacts are not well known but may be relevant when large capacity additions come to their end of life phase. Other issues include accounting for increasingly complex technologies containing small elements. Rare earth elements are almost absent from the LCIs. The life-cycle impact densification in materials should be assessed to prevent loose cut-offs and underestimations. Access to industrial data is often needed but faces intellectual property and confidentiality issues.

As LCIs can be sensitive to the scenario, the scenario could be sensitive to the LCIs, especially if the technology deployment is affected by material supply tensions. For example, reserves, impacts, and criticality of raw materials are valuable information that could be considered in order to adjust the cost of each technology in the TIAM-FR model.

Evolution towards a circular economy is now recognized as a way to achieve the United Nations Sustainable Development Goals (SDGs) [32]. As secondary material resources are expected to play an increasing role in the future [33], investigating their implications in the TIAM-FR model could help achieve more effective resource efficiency policies.

Secondary material resources often feature inferior material quality or purity. For technologies that need to guarantee a quality level, recycling may result in additional treatments, energy, materials, and environmental impacts. LCI-integrated ESMs should thus consider both materials and material quality. This could be done using material flow analysis techniques [34] or thermoecological approaches based on exergy and entropy [35,36].

Conclusion

Combining of the TIAM-FR world energy system model with disaggregated life-cycle inventories enables us to compute prospective life-cycle material requirements of world electricity-generating technologies to 2100. Fossil fuels and metallic and non-metallic raw materials requirements are computed in the construction, operation and dismantling phases of the technologies, providing the first prospective assessment of raw materials requirements by life phase. The results show that the development of solar and wind power could generate an increasing demand for metals and non-metallic mineral raw materials during the construction phase. The method can be adapted to investigate other prospective scenarios, and possibly other energy sectors such as transport and building. Total integration of raw materials into the TIAM-FR model still needs to be developed, as the method presented does not allow raw materials to interact endogenously with the TIAM-FR scenarios. This will require identifying those material-related parameters that may have a significant influence on the scenario trajectory (supply availability, material criticality, etc.). Eventually, prospective life-cycle assessments and energy scenarios could be merged into a single tool in order to devise LCA-oriented energy policies achieving multiple targets.

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