Environmental assessment of energy transition scenarios

Technical file #10

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after nearly 2 years of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

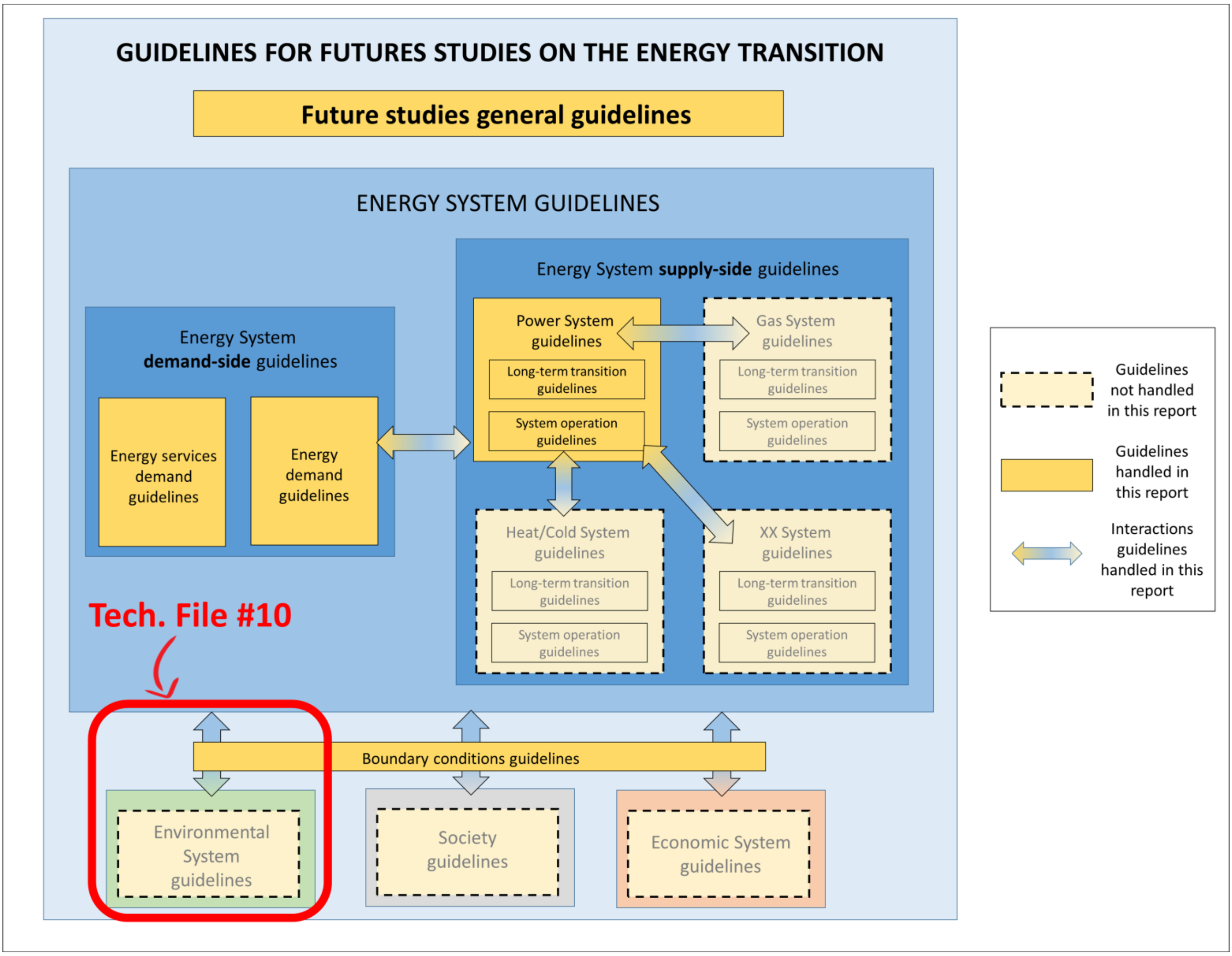
Our project, "Power Systems 2050 – Guidelines for future studies on energy and power transitions," started in January 2018, involved approximately 60 experts through interviews and workshops, reviewed more than 300 works, including about 20 future studies. The objectives and approach of this project are discussed in the executive summary of the framework.

Several aspects of the energy transition are handled in these technical files. However, **on the energy supply-side only the power system has been studied**. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	**Environmental assessment of energy transition scenarios**
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



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Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. Discussing critical interactions with the environment: assessment methods

A. The environment is a surrounding system for human societies

In this report, the *core system* is the energy system or some of its components (such as the power system); surrounding systems are systems in which the core system operates (society, the economy, or the environment). The environment is considered here as a *surrounding system*.

However, the environment has a special position among surrounding systems, as it surrounds both the core system and economic and social systems. By surrounding, we mean that the environment also contains the other systems.

Environment can be defined as follows (André, Delisle, & Revéret, 2009): environment is an organized, dynamic and evolving system composed of natural elements (physical, chemical and biological) and of human elements (economical, political, social and cultural) in which living organisms operate (including human activities) and in which they affect these living organisms (and human activities) either directly or indirectly, immediately or on the longer term.

This definition highlights the inclusiveness of the environment. It also highlights its complex and dynamic nature: organisms act within the environment, which in turn affects the environment, and these environmental changes may affect back the organisms directly or indirectly, following complex feedback loops structures with different temporalities.

Seen from human societies, the effects back on humans may be delayed (such as carcinogenic effects of air pollution, or extreme weather events due to GHG emissions), may happen remotely (such as impacts of climate change which may happen anywhere regardless of where the gaseous emissions took place), they can be combined (such as climate change effects and habitat fragmentation effects on biodiversity, in turn affecting crop productivity), they can be non-linear with threshold effects (such as climate change with regards to the amount of GHG emissions, or unexpected effects on trophic chains due to human activities).

Environment can be described along different space scales:

- Micro environment is at the level of the individual (its habitat for non-human living organisms, its dwelling or neighborhood for human beings)
- Meso environment is at the level of a group of individuals, or society (enlarged habitat, city, region or State)
- Macro environment is at the continent or world level (biosphere, human life)

Human beings have different decision processes and levers at these different scales to perform activities. These activities may interact with their micro or meso environment (local impacts, such as air pollution) or on their macro environment (global impacts, such as climate change or sea level rise, stratospheric ozone depletion, ocean acidification and so on).

In this section, we tackle the following interactions between the energy system evolution and the environment: greenhouse gases (GHG) emissions; impacts on the biosphere; material criticality; land use; air pollution; water use; solid wastes; and noise.

Studies we reviewed generally include considerations on GHG emissions; a few consider air pollution; a few consider mineral resources use (which is a component of material criticality). Other impacts are rarely talked about, and never quantified.

B. Assessing greenhouse gases (GHG) emissions

Greenhouse gases emissions have several global impacts such as climate change and sea level rise. These impacts are global because the atmosphere blends within about a year. Hence no matter where they are emitted, they quickly get blended all around the Earth.

Technically speaking, greenhouse gases are atmospheric gases which intercept infrared radiations from the Earth surface. Some of them are naturally present in the atmosphere, some others only come from human activities; some are naturally present but human activities significantly increase their amount in the atmosphere on the long-term. Increasing their amount on the long-term leads to modify (on the long-term) the radiative balance of the Earth, storing more energy within the Earth system, in turn modifying the stable environment in which ecosystems developed.

Human activities generating GHG's are extremely various today. GHG emissions are usually categorized as follows:

- *energy-related CO_2* emissions, which happen when carbon chains are burnt (under the form of natural gas, biogas, liquid fuels, coal…)
- *process-related CO_2* emissions, which happen during various industrial processes. For example, cement production, glass production, production of various chemicals such as ammonia or nitric acid, steel production, aluminum production etc, release CO_2, outside pure fuel burning (ANCRE, 2013).
- Other *process-related GHG* emissions, which happen during various industrial or agricultural processes. For example, agriculture releases CH_4 and N_2O. Waste disposal emits CH_4. Methane leakage is a commonly neglected source of CH_4 emissions. Leaks happen from natural gas networks (McKain et al., 2015) including pipelines, from coal, gas and oil (including shale oil) extraction. Fossil methane leaks may be estimated to represent between 2.5 and 3% of global methane emissions (Worden et al., 2017).
- GHG emissions or storage due to *Land Use, Land Use Change and Forestry* (LULUCF). CO_2 storage happens through the growth of trees, and CO_2 emissions happen through changes in vegetation covers (afforestation, deforestation, revegetation, management of land…).

The consequences of these processes are various: increase of the global average temperature, sea level rise (because of water dilatation due to this temperature increase and because of ice sheets melting); increase of the frequency and/or magnitude of extreme weather events (droughts, heat waves, storms…)… These consequences are usually called "physical risks"[1].

Future studies logically focus on those GHGs which are emitted by human activities and for which those emissions lead to a significant increase of their amount in the atmosphere. Several practices can be found in future studies when it comes to GHG considerations. They all depend on the driving questions and perimeter of the study.

Within our scope, one study does not consider greenhouse gases (GHG) at all. Its driving questions are about technical aspects of prototypical power systems, and costs of these different systems (ADEME, 2015).

All the other studies include considerations on GHGs. The differences between these studies pertain to the GHG emissions models (that is, their computation in a consistent way vis-à-vis the proposed core system evolution within each scenario) which are used.

- Some studies model energy-related CO_2 emissions only (ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018; ENTSOG/ENTSO-E, 2018). Energy-related CO_2 emissions are those emissions produced when carbon-based fuels are burnt, such as within ICE vehicles, in gas or fuel boilers, in gas or coal power plants, in gas industrial ovens and so on. Usually, the studies considering only energy-related CO_2 emissions focus on the power system only, or on the energy system only.
- Some other studies model process-related CO_2 emissions and other GHG emissions, in addition to energy-related CO_2 emissions (ADEME, 2012; ANCRE, 2013; ECF, 2010; European Commission, 2011; Greenpeace,

[1] Another type of risk is often talked about: transition risks. These risks are actor specific and are linked to the fact of performing an energy transition. They are talked about in terms of inertia of the socio-technical systems which evolve during the transition (in the Future studies section), in terms of stranded assets and sunk costs (in the Economic evaluation section) as well as in terms of desirability (in the Desirability section and employment section).

2015; OECD/IEA, 2017; SFEN, 2018)[2]. Process-related CO_2 emissions are those emissions due to some transformation processes within the industry, such as cement or glass production which emit CO_2 during specific phases of their transformation. The other GHGs which are usually considered are those included in the UNFCCC framework for GHG reporting for countries (UNFCCC, 2014): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3). Those GHG are emitted from agriculture activities, operation of the energy system, some industrial processes and from the use of refrigerants (ANCRE, 2013). The core system of these studies usually is the whole energy system and the agriculture system together.

- Some studies modeling energy-related CO_2 emissions only also roughly quantify the evolution of process-related CO_2 emissions and other GHG emissions in order to provide an all GHG reduction assessment (Association négaWatt, 2014; Fraunhofer ISE, 2015). This rough estimate is largely uncorrelated to the proposed energy system evolution, this is why these emissions cannot be said to be modeled.
- Some studies also include, in addition, the GHG emissions or storage due to Land Use, Land Use Change and Forestry (LULUCF) (Association négaWatt, 2017; European Commission, 2016; IIASA, 2012). These emissions are those due to the fact that different types of lands contain different amounts of stored carbon, so changes in land use and forestry practices may release CO_2, or store carbon. The core system of these studies includes the energy system, the agriculture system as well as the different land uses.

We observe that the larger the core system of the study, the more comprehensive the GHG assessment can be.

One study we reviewed models energy-related CO_2 emissions only for the power system supply-side, but with a footprint approach (Hammond, Howard, & Jones, 2013). This approach further questions the choice of technologies used for the transition to produce, store, transport and distribute electricity.

Recommendations to scenario producers

A strategy about GHGs emissions assessment should be defined and substantiated with regards to the driving questions. The following aspects should be considered:

- Impact definition: GHGs which are included in the assessment
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of these GHGs emissions
- Modeling methodology
- Methodology to tackle horizon effects, or justification they are negligible

C. Assessing impacts on biosphere

The biosphere is the set of all living organisms and their habitats, that is, the set of all ecosystems surrounding us. The biosphere is usually considered as important for human beings for the "ecosystem services" it brings to us.

These services are only the visible part of all the interactions within the biosphere. Within an ecosystem, species interact with each other, and within species individuals interact with each other. Ecosystem services are some of the emergent patterns of all those complex interactions. More specifically, they are the ones which are important to us as human beings. Focusing only on the last links providing the service (for example, focusing on bees for pollination instead of understanding the whole net of ecosystem interactions between bees and their environment, would it be physical, chemical or trophic environment) is a narrow view. It fails to see that the service is actually sustained by a whole set of processes and interactions with other elements of the biosphere. As such, the ecosystem services approach does not enable to uncover all the risks leading to the decline and extinction of the services it aims to study.

[2] (Greenpeace, 2005; Greenpeace, 2012; Greenpeace, 2015; Greenpeace EREC, 2008) are not transparent enough to be sure about their approach.

A classical measure of biosphere integrity is that of biodiversity, a concept which includes the genetic diversity within each species, the diversity of species, and the diversity of ecosystems.

The greatest causes of biodiversity losses are the following (IPBES, 2019):

- Habitat transformation through land use / sea use change. "Agricultural expansion is the most widespread form of land-use change, with over one third of the terrestrial land surface being used for cropping or animal husbandry. This expansion, alongside a doubling of urban area since 1992 and an unprecedented expansion of infrastructure linked to growing population and consumption, has come mostly at the expense of forests (largely old-growth tropical forests), wetlands and grasslands" (IPBES, 2019). Habitat transformation can also happen through habitat fragmentation (e.g. due to the road, or electricity networks), habitat space reduction (due to the proximity of human activities, noises).
- Overexploitation of animals, plants and other organisms mainly via harvesting, logging, hunting and fishing.
- Climate change. "The frequency and intensity of extreme weather events, and the fires, floods and droughts that they can bring, have increased in the past 50 years, while the global average sea level has risen by 16 to 21 cm since 1900, and at a rate of more than 3 mm per year over the past two decades. These changes have contributed to widespread impacts in many aspects of biodiversity, including species distributions, phenology, population dynamics, community structure and ecosystem function" (IPBES, 2019).
- Many types of pollution, as well as invasive alien species, are increasing, with negative impacts for nature. "Marine plastic pollution, untreated urban and rural waste, pollutants from industrial, mining and agricultural activities, oil spills and toxic dumping have had strong negative effects on soil, freshwater and marine water quality and the global atmosphere" (IPBES, 2019).

In freshwater ecosystems, a series of combined threats that include land-use change, water extraction, exploitation, pollution, climate change and invasive species, are prevalent.

No energy transition future study to our knowledge quantitatively assesses the evolution of the biosphere for its different scenarios. However, (Association négaWatt, 2017) provides information about the variation direction of the overall impact on biosphere of its "négaWatt" scenario compared to its Reference scenario. (European Commission, 2011) provides information about the impacts of the energy system on biosphere without explicitly linking those considerations to its different scenarios.

Most likely, computationally modelling biosphere and its integrity is not realistic. However, a qualitative assessment based on demographic evolution, on energy and material extraction, on water use, on land use, on built infrastructure (would it be demand side infrastructure such as roads, or supply-side infrastructure such as hydropower dams) and on the specific environmental practices of the different economic agents may be useful to inform the energy transition debate.

Recommendations to scenario producers

A strategy about biosphere integrity assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: Drivers of biosphere evolution which are considered in the assessment (habitat transformation, exploitation of living organisms, climate change, pollution, invasive alien species)
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of the biosphere evolution.
- Modeling methodology. The methodology can be qualitative in order to trigger discussion with stakeholders and to inform the debate about the interactions between the energy transition and biosphere. *For example, for each considered activity in the scenario, does it improve/degrade habitat, does it increase/decrease the exploitation of living organisms and so on.*
- Methodology to tackle horizon effects, or justification they are negligible

D. Assessing criticality of metals

1. A serious and complex issue rarely addressed in future studies

Metals and more generally materials are, along with fossil fuels, one of the main stock resources that we use on a large scale on the planet. Their use increased significantly in 2009-2010 worldwide. Thus, their supply may face constraints, as summarized in (ADEME, 2017) :

« The exponential growth in demand is likely to outpace the growth in production capacity. As a result, shortages on some minerals could occur in the near future (10 years). With a continuous 2 or 3% demand growth, recycling will not be able to meet this increase and will remain below 20% of the necessary supplies.

In addition, the local environmental consequences of the exploitation of these deposits will limit their social acceptability if they are not properly managed. Moreover, the associated increase in energy consumption in this sector may be deemed incompatible with the fight against climate change. It is probably not the depletion of metals and minerals that is to be feared, but certainly the end of easy extraction and availability. »

Many future studies do not address criticality of metals and materials, even for those describing worldwide transitions which may face material criticality issues, such as scenarios involving major changes including a large share of renewable energy, large storage capacity, and a strong raise of electric vehicles and/or grid reinforcement (such as (Greenpeace, 2015; Lappeenranta University of Technology / Energy Watch Group, 2017; WWF, 2011)). Criticality of metals and materials is now considered as a **blind spot** by a growing number of actors when assessing the technical feasibility of such scenarios.

Among the few studies that quantitatively address these issues is (Association négaWatt, 2018), which presents an assessment of the need for certain materials in its main scenario. (IRENA, 2018) also addresses this question through a global (hence little transparent) material consumption indicator computed by E3ME model (Cambridge Econometrics, 2019).

More generally, research on these constraints is quite limited compared to the obvious importance of the subject. This field of research is nevertheless developing: (Bonnet, Carcanague, Hache, Seck, & Simoën, 2019) provides a graph of the annual number of academic publications on these issues that shows a growing interest by the science community; but the study also concludes that it is difficult to reach a consensus on the supply risk associated with a raw material because there is a high sensitivity in the results according to methods and data.

2. Criticality: a multidimensional analysis of dependance on mineral resources

Dependence on mineral resources is commonly referred to as "criticality". The study of the constraints on the supply of a material resource is complex because those constraints are multidimensional. Indeed, taking into account the technical aspect alone does not allow to properly assess the criticality level: there are critical materials that are not rare, as well as critical materials that can be recycled.

Thus, as summarized in (Bonnet, Carcanague, Hache, Seck, et al., 2019) :

« Criticality is neither universal, nor timeless, nor binary (Graedel and Reck, 2016). It actually varies according to the economic (commercial, technological, financial) and political (security, defence, foreign policy) interests of a State. It is also a key element in the State's relations with its partners on the international scene. The need to take the geopolitical dimension into account and to refine its quantitative and qualitative measurement in criticality studies thus appears to be an essential challenge for both the researcher and the decision-maker. »

Criticality can thus be seen as a **combination of risks**, of a geopolitical, economic, production, environmental or social nature.

3. Main metals categories and essential metals for the energy transition

(ADEME, 2017) provides in its appendices a clear classification of metals. A first important distinction is related to their concentration in the earth's crust:

- Above 1000 ppm, there are so-called **"abundant" metals**, such as silicon or aluminium.
- Between 1 and 1000 ppm, these are **rare metals**. There are many, including lead, copper, zinc, nickel, cobalt, molybdenum and tungsten.
- Below 1 ppm are the **"very rare" metals**. These include "precious" metals (gold, silver and the 6 platinoids) and 3 other metals: antimony, selenium and indium.

"Rare earths", another important category of elements, refers to a specific group of 16 or 17 elements including the 15 elements of the lanthanides series (57 to 71) and yttrium. All have similar properties and are almost always associated in their deposits. Scandium is sometimes added to the list. Rare earth are in fact not so rare but their deposits have the particular characteristic of being very localized (see (ADEME, 2017) for a more complete categorization).

The various technologies implemented in different energy transition scenarios each require certain amounts of different metals: the solar photovoltaic systems require silicon, silver, tellurium, galium and indium, batteries use lithium, nickel, cobalt, among others, grid reinforcement require copper, certain types of wind turbines and electric cars require rare earths (neodymium, praseodymium and dysprosium in particular) for their permanent magnets, hydrogen vehicles require platinoids, etc.

Here is a description of the current situation for a few metals generally involved in energy transitions proposed in future studies:

- As far as the rare earths situation is concerned, two key figures should be retained. On the one hand, about 90% of current production takes place in China, and on the other hand, about 80% of the demand is generated by permanent magnets production, which are then used for electric motors and wind turbines production. Thus, the analysis of criticality necessarily involves a geopolitical aspect. For this purpose, see the study "Rare Earths and China: A Review of Changing Criticality in the New Economy" (Seaman, 2019).

- Concerning lithium, geological criticality does not seem to be particularly constraining. On the other hand, as for rare earths, geopolitical criticality is a reality. Indeed, lithium is produced in a very concentrated way, mostly in the "lithium triangle", i.e. in Bolivia, Chile and Argentina by a very few companies. Also, the share of lithium demand generated by battery production is significant and is expected to increase. Regarding this metal, see, for example, the study "Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport" (Hache, Seck, Simoen, Bonnet, & Carcanague, 2019).

- For copper, by contrast, some constraints from geological criticality are expected. As presented in the study (Bonnet, Carcanague, Hache, Seck, et al., 2019), a significant portion of copper demand comes from the electricity sector. For a modelling of geological criticality on copper, combining increased demand and the development of recycling processes, see the SURFER project led by the CNRS, BRGM and ADEME.

- Finally, for other materials such as cement, see the study "The impact of Future Generation on Cement Demand: An Assessment based on Climate Scenarios" (Bonnet, Carcanague, Hache, Simoen, & Seck, 2019), or the study (United States Department of Energy, 2015) which provides tables about the material consumption of different energy production technologies and different types of vehicles.

4. The basics for conducting a criticality analysis in future studies

As mentioned, criticality is a multifaceted parameter. Here is a set of criteria and questions[3] that can arise in the analysis of the criticality of a metal in a scenario (also works with other materials):

- **Geological availability**. *Is the metal abundant, rare, or very rare?*
- **Geological dependence between materials.** *Does the metal mining depend on the mining of another metal?*
- **Dynamics of production development.** *How long does it take from the first studies on a deposit to its full commercial exploitation?*
- **Recycling process.** *Do we know how to recycle this metal? At what rate? What are the recycling capacities?*
- **Substitution possibilities.** *Are there easy substitutes – would it be another material or another technology which does not require this metal, for the same use?*
- **Demand growth**
- **Concentration of production.** *How many companies produce this metal?*
- **Political risk**
- **Social constraints**, including the availability of water for the production of ore and desirability issues raised by local populations with respect to the impacts of its exploitation (Donella H. Meadows, Randers, & Meadows, 2004).
- **Environmental constraints.** The notion of environmental constraints enables to introduce the impact of climate change on mineral mining activities. Indeed, as developed in the study (Carbone 4, 2019): "mining activity is by its very nature particularly exposed to climatic hazards and in particular to water resource management issues. "This illustrates how different environmental problems can be linked.
- **Concurrent uses.** Metals are not only used as part of the energy transition. The Defense sector, for example, requires rare earths. This may make the studying of criticality even more complex.

As far as future studies are concerned, some of these aspects directly derive from scenario storylines and boundary conditions while other may be modelled (such as the development of recycling chains, some substitutions or the geological dependence between materials). Hence some aspects may be tackled in a qualitative way while others may be quantified[4,5].

[3] To go a step further in criticality analyses, see the links to studies cited above such as the SURFER project, or the study (Bonnet, Carcanague, Hache, Seck, & Simoën, 2019) which presents an analysis of the criticality of energy transition materials in general, based on IEA models, and then an analysis on the criticality of copper lithium using the TIAM model.

[4] The European Commission released a table of the metals it considers as critical (Commission européenne, 2017). This table informs about 27 metals, including their main producing countries, their substitution index and their recycling rate. It can be an interesting source of data for quantitative analyses in scenarios.

[5] Metal supply issues are fast-changing topics, especially in the last few years, and the literature on these issues is not yet well developed. As a result, some of the data used may be **obsolete**. In fact, some publications rely on data from other publications, etc. with databases that are too old to be up-to-date.

5. Recycling is a key lever but has inherent limits

Recycling describes the use of a material within a waste as an input for good production processes[6]. It is an important tool to reduce the criticality of metals and materials. As any tool it has limits, but its development can be fostered by several mechanisms. The rate of development of recycling chains compared to the consumption growth rate of the material is a key parameter if recycling is to reduce criticality[7].

The following mechanisms play a role in this rate of development:

- **Market mechanisms** leading (or preventing) the development of recycling sectors. In this case, the metal price on the markets is an important factor: if the price of extracted metal is lower than recycling costs for this metal, then the incentive to develop recycling facilities is low.
- **State regulations**. The recycling market has the advantage of being quite predictable: the need for recycling photovoltaic panels, for example, follows the panel production rhythm with a lag that reflects the average lifespan of a panel. Hence forward planning and regulations may be adapted to foster recycling. Among the tools that can foster the development of recycling industries we can mention: financial guarantees for each installation to cover the costs of dismantling in the event of the operator's bankruptcy; the principle of Extended Producer Responsibility (EPR), which imposes to the company that places the technology on the market to pay a participation at the moment of its launch to finance its recycling through appropriate processes once the product reaches the end of its life; regulations on the recycling rate, etc.
- Country or region-specific **reputational risks**, which may put pressure on the reputation of the manufacturer or operator of the technology to be recycled.

Besides the natural inertia behind designing and producing whole recycling industries (including collection, transport, sorting and transformation of materials), recycling has inherent limitations: a **100% recycling rate cannot be achieved** because of unavoidable losses at each recycling step, each subject to various inefficiencies (collection, sorting, transport, various transformations, etc).

Under some conditions, materials are not recycled because too much energy would be required (translating into too expensive recycling processes) to make all the transformations required to produce back the material as it used to be when it was first used as an input in the goods production process (that is, refined enough). This is the case when materials are intimately blended together for specific uses, or when materials are dispersed in small quantities in complex products (such as electronic circuits (The Shift Project, 2018)).

Some production processes require pure materials in order for the end-products to fulfil their specifications and performances (such high performance steel in car industries), sometimes constraining the use of recycled materials. When pure enough input material cannot be obtained from recycling, new pure material can in some cases be added in the input; or, the less pure material can be used for producing other goods requiring lower quality material (in this case the material is said to have undergone a "functional loss").

Besides, recycling has different impacts on the environment: different types of industrial processes are involved (mechanical, chemical, thermal recycling, etc.), all consuming energy and, directly or indirectly, releasing pollution, including GHG's. In most cases, metal produced through recycling leads to lower environmental impacts than metal produced directly from extraction, but still has some impacts.

Material sobriety impacts the overall need for materials per year, hence it decreases both the need for recycling and for material extraction, leading to an overall decrease in the various environmental impacts of both activities. As a consequence, narratives about mechanisms leading to material sobriety may also be produced in scenarios addressing the criticality issue (such as in (Association négaWatt, 2018)).

[6] Whereas **material efficiency** measures the amount of a given material required to generate a unit of added value within a given set of industrial processes, no matter the origin of the material (recycled or not). For example, scrap metal generated during production activities and reinjected within the same, or other, production activities, is part of an increased material efficiency for goods production. It is not considered as recycling.

[7] For an example of modelling that integrates the notion of recycling, see the SURFER project led by the CNRS, BRGM and ADEME. This modelling highlights that the rate of development of recycling industries is a decisive parameter.

Different indicators can be used to quantify recycling of a material, such as:

- **End-Of-Life Recycling Rate** (EoL RR) is the share of materials contained in end-of-life products that is collected, pretreated and finally recycled for reintroduction into the cycle. This is the indicator commonly referred to as the "recycling rate".
- **Recycling Input Rate** (RIR) measures the proportion of metal produced by recycling processes in the total production of this metal.

Recommendations for scenario producers

A strategy about material criticality assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: materials and metals which are considered in the analysis; specific aspects of criticality which are investigated (geological availability, dynamics of production development, demand growth, recycling etc.).
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as involved in material criticality (different industries, including recycling industry).
- Modeling methodology. The methodology can be qualitative in order to trigger discussion with stakeholders and to inform the debate about the interactions between the energy transition and material criticality. Methodological guidance can be found in (Bonnet, Carcanague, Hache, Simoen, et al., 2019). If recycling happens in the described scenarios, mechanisms fostering its development should be discussed (state regulation, market mechanisms, reputational risks…); and the monitored performance indicators should be precisely defined.
- Methodology to tackle horizon effects, or justification they are negligible

E. Assessing land use change

Land use and land use change impacts are by essence local (they happen where the land is used). However, these impacts may be indirect, such as when agricultural production switches from food use to biofuel production use (no direct land use change), triggering in turn deforestation to farm in order to produce the missing food (indirect impact).

As previously mentioned, land use changes have significant impacts on carbon emissions or storage, as different types of soil and vegetation store more or less carbon. They also have impacts on the biosphere. Furthermore, those changes may be more or less desirable by local populations (see section on desirability).

As previously described, the drivers of land use change at the world level is agriculture. However, energy system evolution may also greatly affect land use both through supply-side installations[8] and through demand-side evolutions.

Concerning the former aspect (supply-side), land may be differently occupied by supply-side installations: either land is entirely dedicated to the installation, or it can be used for other purposes (Criqui, 2013). For example, ground PV installations may cover other activities from the Sun, hydropower dams may be used for irrigation and leisure activities (or even for installing floating PV panels), and so on. Some installations may also reduce the number of activities which can be performed on their land, causing land use conflicts (and desirability issues). For example, off-shore installations may cause conflicts with fishery activities. Supply-side evolution may also lead to evolutions in biofuel production, or energy wood production. These productions are actually photosynthesis

[8] For a comprehensive assessment of the space required to extract and refine primary energy, see (Smil, 2015).

exploitation through agriculture and forestry. As such, their evolutions may lead to direct or indirect land use changes.

Concerning the latter aspect (demand-side), as explained in the lifestyles and consumption section, urban planning and transportation networks are two key technical and organizational systems which influence energy demand.

A few studies assess the evolution of land uses per say (that is, not only for computing LULUCF GHG emissions) either qualitatively or quantitatively through the area of land used by the energy, or power, system supply-side (ADEME, 2015; ANCRE, 2013; Association négaWatt, 2017).

Recommendations to scenario producers

A strategy about land use change assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: specificities of lands (area, current land use(s), types of land…). For example, does the study only assess total surface of land use change, or does it assess land use change along different types of lands (forests, marshlands, croplands…), or does it assess the nature of the changes (e.g. from fishery to electricity production)?
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of land use changes.
- Modeling methodology. The methodology can be qualitative in order to trigger discussion with stakeholders and to inform the debate about the land use changes involved by the proposed energy transitions. Desirability aspects such as impacts on human ecology or on employment may be discussed. Such discussions are much more concrete than the sole indication of the total surface of land which changed during the transition.
- Methodology to tackle horizon effects, or justification they are negligible

F. Assessing air pollution

Air pollution may be defined as any atmospheric constituent present as a result of anthropogenic activity or natural processes that causes adverse effects to humans, animals, vegetation, or materials. Air pollution is an impact on the meso-environment (typically, city scale).

The main adverse effects usually considered in the public debate are effects on human health (respiratory and cardio-vascular diseases, cancers) and acid rains. According to the World Health Organization, 1.3 million people die each year for air pollution reasons in the world (« OMS | Effets sur la santé de la pollution de l'air en milieu urbain », 2019).

The main air pollutants which are considered in national legislations and in future studies are the following (IIASA, 2012; Liu, 2015):

- Sulfur dioxide (SO_2). It affects human health and it is a precursor to acid rains and particulate matter. It is produced by the burning of fossil fuels contaminated with sulfur compounds (such as coal or heavy oil) and copper extraction.
- Nitrogen oxides (NOx). It affects human health and it is a precursor to acid rains. It is produced through the combustion of fuels at high temperature such as in ICE vehicles or power plants, and through agricultural fertilization.
- Carbon monoxide. It is a highly toxic gas, inhibiting respiratory functions. Carbon monoxide poisoning is the most common type of fatal air poisoning in many countries (Omaye, 2002). It is mainly produced by ICE vehicles.
- Volatile organic compounds (VOC). They have effects on human health. They can have anthropic sources such as the use of various chemicals such as paints and coatings, ICE vehicles and other sources.

- Particulate matter PM2.5 and PM10. They are particles which can be inhaled and are classified by size. The smaller the particle, the deeper in the lungs it can get. They affect human health. They are produced by industrial combustion, agriculture, ICE vehicles, and construction industry, under the form of dust, soil, soot or smoke.

Some of these pollutants interact with each other and with other atmospheric components (called precursors) to produce secondary air pollutants following complex interactions.

A few studies model air pollution: (IIASA, 2012; OECD/IEA, 2017) use the GAINS model to do so. (ADEME, 2012) uses another model first computing the emissions of primary pollutants and precursors of secondary pollutants, and then assessing air quality in urban areas through a second module.

Recommendations to scenario producers

A strategy about air pollution assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: air pollutants which are considered in the study
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources, or precursors of the pollutants (both primary and secondary)
- Modeling methodology
- Methodology to tackle horizon effects, or justification they are negligible

G. Assessing water use

Water use may affect sea water and/or freshwater; freshwater can be running water or fossil water (non renewable water, typically groundwater in an aquifer). It may affect water quality and/or water flow. Water quality can be measured along several dimensions (temperature, pH, amount of dissolved oxygen, amount of toxic substances…). Water use has local impacts.

Water use affects the biosphere. For example, thermal power plants (nuclear or fossil fuel power plants) need a cooling source to properly operate. Some of them use water as a cooling source, in turn releasing water that is warmer than the ambient water. Local ecosystems may be sensitive to these releases. Legislations control local water temperatures, sometimes leading to power plants' temporary shutdown in case of heat waves. Hydropower dams also have impacts on the biosphere (other than the direct submersion of the local ecosystems), preventing sediments and species to move freely.

Water use can also directly affect human activities (fishery, irrigation, industrial cooling, leisure activities…), or human direct water consumption, hence rising water use conflicts and desirability questions.

Water is used in nearly all industrial processes within the energy sector (extraction, processing of fossil fuels and uranium, biomass production and conversion, thermal, nuclear, geothermal, hydro- electricity production). As a result, the energy sector represents nearly 50 % of water withdrawal in developed countries[9] (Lemoine, 2016).

No future study about energy transition quantitatively tackles the question of water use to our knowledge. Some studies provide qualitative considerations about this aspect: (Association négaWatt, 2017) qualitatively considers the variation direction of water consumption in its "négaWatt" scenario compared to the Reference scenario. (European Commission, 2011) provides qualitative considerations on this aspect without linking them explicitly to its different scenarios.

[9] Water withdrawal is the amount of water withdrawn from a source whereas water consumption is the amount of water which is not released back in the source.

Recommendations to scenario producers

A strategy about water use assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: specificities of the water which is used (sea water, freshwater); specific indicators which are used (volume of consumed water, water temperature…)
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of water use
- Modeling methodology. As the considered impacts are local, local conditions would have to be known in order to precisely assess and discuss the impacts of water use evolution. As a result, qualitative general considerations can be provided and some case studies could be examined to illustrate specific effects of the proposed energy transition. Important aspects to discuss are impacts on biosphere and desirability aspects (for individuals and businesses).
- Methodology to tackle horizon effects, or justification they are negligible

H. Assessing hazardous and nuclear solid wastes production

Solid wastes are of various natures. However some of them can be reused, or recycled, or incinerated, biologically or chemically treated. After these options, some wastes remain and are landfilled. Part of these wastes are categorized as "hazardous", other as non-hazardous, with regards to the landfilling practices (Méhu, 2016). Ultimate nuclear wastes[10] are treated, stored and landfilled in separate processes.

These solid wastes have local impacts if properly stored. They may have impacts on the meso-environment in case leachate risks[11] are not properly managed, polluted water then circulating in the environment. However, several practices are applied to avoid leachate being formed and being released in the environment: waste can be vitrified, as is performed for nuclear waste, preventing any contact with water, or landfills can be equipped with leachate collection and treatment systems.

Numerous activities linked with the energy system generate **hazardous wastes** (SEPA/Environment and heritage service/Environment Agency, 2003): different activities in fossil fuels extraction and transformation/refining; combustion of fossil fuels in power plants and in industrial processes generate ashes and residues which ultimately have to be landfilled; end-of-life vehicles contain different substances considered as hazardous; some end-of-life batteries are hazardous waste… These wastes have various effects on, or pose various risks for, human health and the environment in case of direct exposure (Directive 2008/98/EC on waste, 2008): they can be explosive, highly flammable, irritant, harmful, toxic, carcinogenic, corrosive, infectious, mutagenic, ecotoxic…

Nuclear industry generate **nuclear wastes**, during and after uranium extraction, uranium treatment and enrichment, residues from nuclear power production, radioactive waste from power plant dismantling. These wastes are categorized according to two criteria: radioactivity level and radioactivity duration. These wastes mainly have long-term carcinogenic effects on humans, and living organisms, in case of direct exposure (« Answers to Frequently Asked Questions (FAQs) by UNSCEAR », 2019).

A few future studies on the energy transition consider solid waste. (Association négaWatt, 2017) estimates the variation direction of the amount of waste (without waste distinction) produced from its Reference scenario to its négaWatt scenario. (European Commission, 2011) assesses the variation direction of the amount of nuclear waste which will have to be managed in its different scenarios, compared to its Reference scenario.

[10] That is, those which are considered as not usable in future industrial processes.

[11] Leachate is water which passed through the waste and extracted soluble or suspended solids within the waste.

Recommendations to scenario producers

A strategy about hazardous and nuclear waste assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: specificities of wastes which are considered (hazardous or not, nuclear, type of effect on human health or the environment, radioactivity level, radioactivity duration…). *For example, does the study only assess the total amount of solid waste from the energy sector, or does it assess the amount of nuclear, and hazardous waste?*
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of the considered wastes.
- Modeling methodology. The methodology can be qualitative in order to trigger discussion with stakeholders and to inform the debate about waste generation and management involved by the proposed energy transitions. Desirability aspects may be discussed. Such discussions are much more concrete than the sole indications of the total amount of generated waste during the studied transitions.
- Methodology to tackle horizon effects, or justification they are negligible

I. Assessing noise

Noise can be defined as annoying sound, which is a partly subjective definition. However, above a certain volume level, any sound is annoying for human beings (« Bruit. Définitions—Risques—INRS », 2019). Noise is a local impact, as sound level rapidly decreases with distance to the sound source.

Noise has effects on health, mainly on auditory capacities, and generates stress and sleep problems.

Noise is generated by air movement, hence technically any process involving movement can be a source of noise. However, as noise has a subjective definition, it has to be linked with desirability questions. Most commonly considered sources of noise within the energy system is noise from passenger or freight transportation (ground or air transportation), and from the operation of some power plants (such as wind turbines).

Noise is not considered in the future studies we reviewed.

Recommendations to scenario producers

A strategy about noise assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: what specific aspects of noise are considered
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as noise sources
- Modeling methodology. As the considered impacts are local, local conditions would have to be known in order to precisely assess and discuss the impacts of noise. As a result, qualitative general considerations can be provided and some case studies could be examined to illustrate specific effects of the proposed energy transition. An important aspect of noise impact is the desirability for individuals.
- Methodology to tackle horizon effects, or justification they are negligible

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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