SCORELCA

STUDY N° 2017-02

ENERGY TRANSITION SCENARIOS : STRENGTHS AND WEAKNESSES OF LCA IN A RESOURCE-LIMITED CONTEXT

SYNTHESIS

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SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

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Introduction

Faced with the challenges of sustainable development and the fight against global warming, strategies have been multiplied, at both international and regional levels, with the aim of developing evolution scenarios that (in theory) should limit global temperature increases.

The various energy transition scenarios do not represent predictions, but allow the scope of possibilities in terms of energy demand and production to be studied, in particular with a view to defining the actions to be taken to achieve a fixed climate objective. However, despite the development of sophisticated energy transition scenarios, it seems difficult to understand the problem of resource depletion.

Life Cycle Assessment (LCA), as a multi-criteria reference methodology, has a key role to play in assessing the environmental impacts of transition scenarios. In particular, it can make it possible to "couple" in a precise, extensive and quantified way the transition scenarios and the flows of resources and energy necessary for this transition, and thus to make an important contribution to the debate on the resource issue. However, methodological and data issues need to be resolved, both on the resource depletion indicators used and on the prospective side, so that the LCA results can provide a relevant answer to the question of resources in the energy transition.

In this context, SCORELCA and its members wanted to conduct this study in order to better understand the impact of the energy transition on the problem of resource depletion and to understand the strengths and weaknesses of LCA in evaluating these scenarios. Thus, the specific objectives of this study are:

- Carry out a detailed analysis of the work on the subject "resources issue and energy transition"
- Define a set of recommendations for the application of LCA to energy transition scenarios with a focus on the issue of "resource depletion
- Apply LCA to a set of assumptions for an existing energy scenario (e. g. IEA 2°C scenario) and illustrate some of the established recommendations.

This study has a theoretical but above all a practical aim: this is why, after a bibliography phase and a phase of recommendations on the best ways to use LCA to evaluate an energy transition scenario, the study will be carried out through a specific application case.

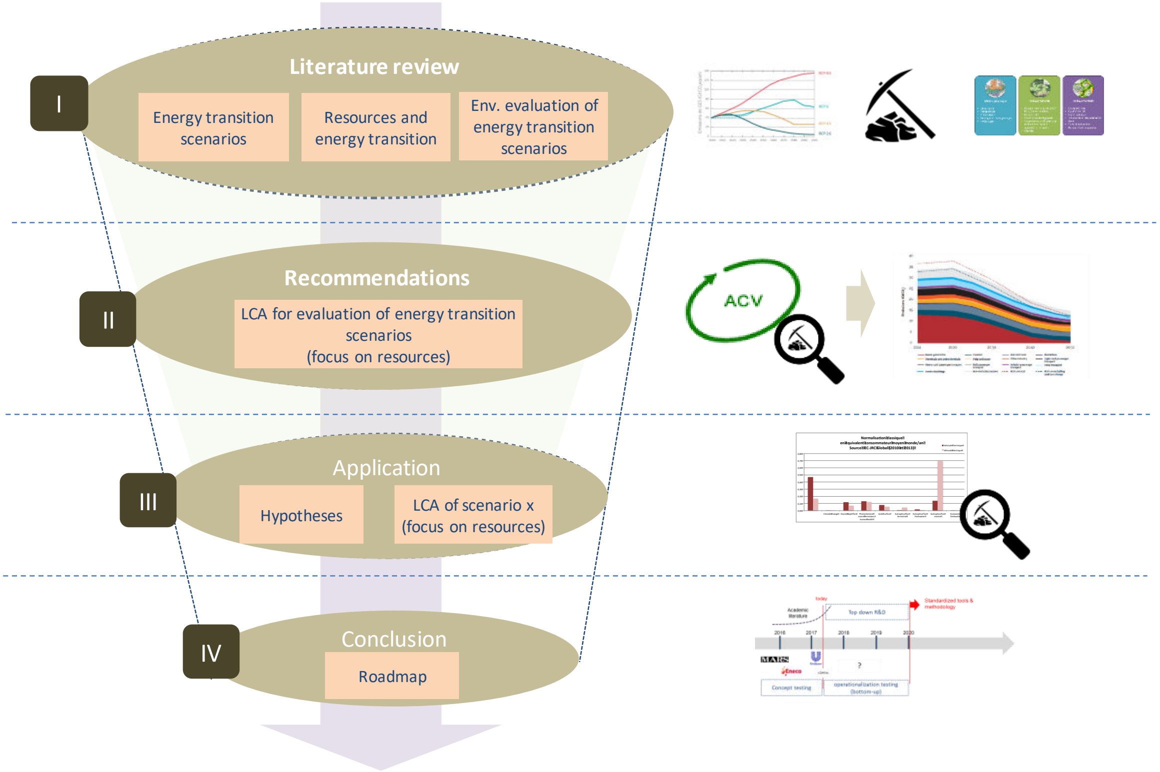


Figure 1 : Methodological approach for the study

I. Bibliography

1. State of the art of energy transition scenarios

An energy transition scenario is a projection of energy demand and supply and the corresponding Greenhouse Gases (GHG) emissions, in an identified perimeter in terms of time and space. By proposing pathways with detailed energy consumption and production, the challenge of a scenario is not to predict the future, but to explain how to achieve a series of objectives by revealing their conditions of success as well as other structuring assumptions. An energy transition scenario aims to reduce GHG emissions due to energy production and consumption, in line with specific objectives such as limiting global warming to 2°C.

In order to meet the objectives of the study, the following scenarios were specifically analyzed:

Table 1 : Features of the studied scenarios

Scenario Name	Time Horizon	Primary Energy Mix			Final Energy Consumption	Greenhouse Gases Emissions	Comments
		Renewable Energy	Fossil Energy	Nuclear			
IEA – ETP 2DS	2060	**52%** Renewable 25% (excluding biomass and hydropower) Biomass 22% Hydropower 5%	**35%** Oil 15% Natural Gas 13% Coal 7%	**12%**	430 EJ in 2060 (+6% compared to 2014)	9 GtCO2 in 2060 (-61% compared to 2014), 19 GtCO2 in 2040	Focused on technological prospective, and not based solely on technologies profitability
IEA – WEO Sustainable Development	2040	**30%** (including hydropower and biomass)	**60%** Natural gas 24% Oil 23% Coal 13%	**10%**	425 EJ (10 173 Mtep, +7% compared to 2016)	18.3 GtCO2 in 2040 (-42% compared to 2016)	Focused on climate policy, access to energy and air quality improvement
BP – Faster Transition	2040	**33%** Renewable (excluding hydraulic) 25% Hydraulic 8%	**60%** Oil 25% Natural Gas 22% Coal 13%	**7%**	*669 EJ (graphic read) [Primary Energy]* Yet, a graph shows an increase in primary energy consumption of about 25%	25 GtCO2 in 2040 (-24% compared to 2016)	Mid-term prospective, and no target to fulfill the Paris agreement
Greenpeace – Energy [R]evolution	2050	**76%**	**24%**	-	289 EJ in 2050 (-11% compared to 2012)]	4.4 GtCO2 in 2050 (-80% compared to 1990)	Focused on renewable energy and plans nuclear power shutdown
Shell – Sky	2070	**67%** including : Solar 32% Wind 13%	**22%** Oil 10% Natural Gas6% Coal 6%	**11%**	*No figure, but a doubling of world energy consumption by 2070*	Carbon Neutrality by 2070	Focused on climate policy and access to energy. Major improvements thanks to technology
World Energy Council – World Energy Scenarios (Unfinished Symphony)	2060	**36%** 19% Biomass 13% other renewable 4% Hydropower	**51%** 24% Gas 22% Oil 5% Coal	**13%**	478 EJ (+21% compared to 2014)	12.6 GtCO2 in 2060 (-60% compared to 2014)	Focused on climate policy, “moderate but smart growth” and strong international and regional cooperation
WWF – Ecofys Energy Scenario	2050	**95%**	**5%**	-	-26% compared to 2014	About 4 GtCO2 en 2050 (-80% compared to 1990)	Focused on renewable energy and plans nuclear power shutdown

It should be noted that the level of detail of available data for the various scenarios is not the same. Thus, the NGOs' scenarios, WWF and Greenpeace, and especially those of the IEA, can be considered as very transparent in terms of assumptions made, unlike the scenarios of BP, Shell or World Energy Council. In addition, the various scenarios are also very sensitive to the technological assumptions adopted (*Carbon Capture and Storage (CSS)* diffusion starting from 2030 in the IEA scenario for instance).

Thus, the scenario chosen for LCA application to a transition scenario is the IEA's Energy Technology Perspective (ETP) 2DS, namely because the energy and GHG emissions pathways of the different sectors are very detailed and allow to conduct more precise analyses. In addition, this scenario is often used as a 2°C reference study case by several international initiatives such as the *Science-Based Targets initiative* (SBT) or ACT (Assessing low-Carbon Transition).

2. State of the art of existing and ongoing work on the subject of "energy transition and resources"

The issue of the availability of the materials needed for the energy transition is not a brand new one. Indeed, energy transition will require the construction of power generating facilities and will thus consume traditional building materials (iron, concrete, cupper, etc.) but also materials that have not been used much so far, yet necessary for some technologies, many of which still emerging.

According to the IEA's *Energy Technology Perspectives* scenario, 56% of global energy consumption in 2060 will rely on low-carbon technologies (including renewable technologies), with demand in solar and wind energy hitting 39,000 TWh by 2060. As of today, the quantities of materials needed to build these new facilities diverge from one source to another, mainly because of the uncertainty on the market shares evolution of the different technologies. In addition, the historical data for some metal extractions are not available, making it impossible to build a reliable model predicting the evolution of materials demand.

Thus, the review of existing literature highlighted that numerous authors (ANCRE, 2015; Bonnet, Carcanague, Hache, Seck, & Simoen, 2018; Geldron, 2017; Hache, Simoen, & Seck, 2018; L'Usine Nouvelle, 2018; Lepesant, 2018; Vidal, 2018; Vidal, Goffé, & Arndt, 2013; World Bank Group, 2017) focus on the evolution of the various parameters constituting the resources market and try to address to some concerns, namely :

- Is there a real resources depletion risk within the coming years?
- What mineral resources are involved?
- How can this risk be mitigated?

Vidal's study (Vidal et al., 2013) included in the ANCRE report estimates the needs by technology or by sector for some materials:

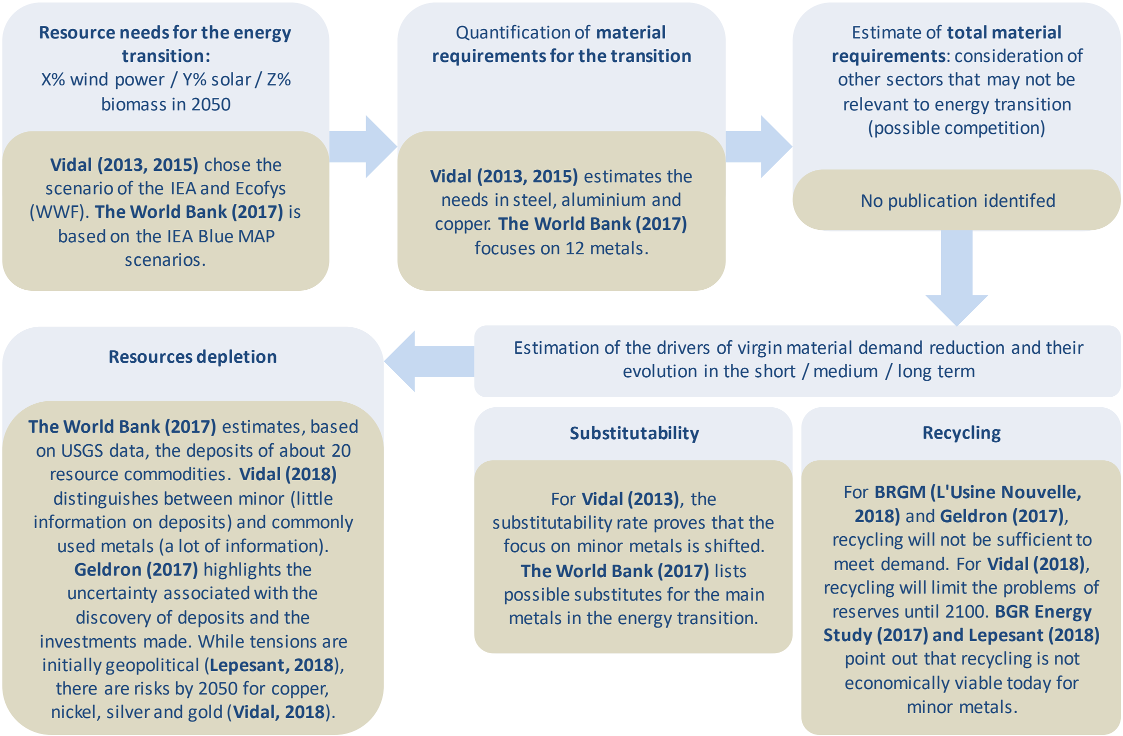
- In an energy transition following the IEA and Ecofys (WWF) scenarios, the ANCRE estimates a "raw materials consumption (steel, copper, aluminium, concrete and glass) equivalent to 2 to 8 years of the 2010 world production" (ANCRE, 2015) for the only sector of electricity production from wind and solar power.
- Under the same scenarios, the authors estimate the following needed quantities for the next 40 years, once again for wind and solar power generation:
    - 3,200 millions tonnes of steel
    - 310 millions tonnes of aluminium
    - 40 millions tonnes of copper
- These estimates represent an annual increase in the overall production of these metals from 5 to 18%.

The *Global Material Resources Outlook* (OECD, 2018) estimates the raw materials quantities consumed until 2060, based on the economic model ENV-Linkages developed by the OECD and not on an energy transition scenario. **This estimate foresees an increase from 89 Gt of consumed materials in 2017 to 167 Gt in 2060.** In particular, projections for metal ore anticipate an increase from 9 Gt in 2017 to 20 Gt in 2060, and for non-metallic metals an increase from 44 to 86 Gt.

As a result, there is no consolidated view of the impact of energy transition scenarios on the overall mineral resources. This is due to the variability of energy transition scenarios, but also to the different technological pathways considered, as well as to the lack of historical data for certain types of metals. Some research projects, particularly in France (SURFER and GENERATE), were launched in order to investigate this issue of quantifying raw materials needs for the energy transition.

Although it is difficult to talk about depletion, the studied literature identifies a set of minerals for which tensions seem to be predictable by 2050. “Shortages on a long period are to be considered, due to the lack of a sufficiently rapid development of new deposits. This could be the case for **antimony, zinc or copper**” (Geldron, 2017), but also the case for **cadmium, cobalt and lithium** (Moreau, Dos Reis, & Vuille, 2019). According to Vidal, tensions are to be expected by 2050 for **copper and nickel,** but especially for **gold and silver**, for which the currently exploited deposits are of very poor quality. Finally, the major determinant is economic and is linked to geopolitical circumstances (Lepesant, 2018), but the uncertainty remains strong.

The figure below summarizes the analysis framework on the issue of materials for energy transition, and the different studied publications are located according to their theme.



Resource needs for the energy transition:
X% wind power / Y% solar / Z% biomass in 2050

Vidal (2013, 2015) chose the scenario of the IEA and Ecofys (WWF). **The World Bank (2017)** is based on the IEA Blue MAP scenarios.

Quantification of **material requirements for the transition**

Vidal (2013, 2015) estimates the needs in steel, aluminium and copper. **The World Bank (2017)** focuses on 12 metals.

Estimate of **total material requirements**: consideration of other sectors that may not be relevant to energy transition (possible competition)

No publication identifed

Estimation of the drivers of virgin material demand reduction and their evolution in the short / medium / long term

Substitutability

For **Vidal (2013)**, the substitutability rate proves that the focus on minor metals is shifted. **The World Bank (2017)** lists possible substitutes for the main metals in the energy transition.

Recycling

For **BRGM (L'Usine Nouvelle, 2018)** and **Geldron (2017)**, recycling will not be sufficient to meet demand. For **Vidal (2018)**, recycling will limit the problems of reserves until 2100. **BGR Energy Study (2017) and Lepesant (2018)** point out that recycling is not economically viable today for minor metals.

Resources depletion

The World Bank (2017) estimates, based on USGS data, the deposits of about 20 resource commodities. **Vidal (2018)** distinguishes between minor (little information on deposits) and commonly used metals (a lot of information). **Geldron (2017)** highlights the uncertainty associated with the discovery of deposits and the investments made. While tensions are initially geopolitical (**Lepesant, 2018**), there are risks by 2050 for copper, nickel, silver and gold (**Vidal, 2018**).

Figure 2 : Synthesis of the bibliography analysis on resources issue in the energy transition

3. Environmental assessment of energy transition scenarios

In a context of the development of a large number of energy transition scenarios, the issue of the environmental impact (in the broad sense of the term) of these scenarios is rarely addressed. However, the consequences on other environmental issues than climate (resources depletion for instance) can be significant, and it is therefore essential to assess the implemented public policies from a multiple-criteria perspective (Patouillard, 2018; Sala, Farioli, & Zamagni, 2013).

The energy transition environmental assessment appears complicated because of the large amount of data to be collected. Indeed, the aim is to assess over time a global and dynamic system, which processes interact with each other. As a result, energy transition scenarios usually do not consider energy technologies life cycle and the LCAs mainly consider only one technology at a time (Hertwich et al, 2015). Yet, LCA considerations for energy transitions studies make it possible to evaluate the potential of transferring impacts, be it in terms of pollution or consumption of non-renewable resources (Hammond, Howard, & Jones, 2013; Harmsen, Roes, & Patel, 2013; Hertwich et al., 2015) with regard to the GHG emission reduction goals in the scenarios.

In summary, the use of LCA for a transition scenario assessment is still not widespread in the literature, due to its complexity. Some authors take into account the resources issue (Bohnes, Gregg, & Laurent, 2017), yet without linking it to their potential depletion. Two studies are of particular interest for the purpose of this mission: first, Hertwitch et al. (2015) who carried out a comprehensive multi-criteria LCA analysis on two of the IEA scenarios, with some data that could feed our own LCA (inventory parameters for instance); second, Harmsen et al. (2013) who provides an interesting approach to characterize resources depletion through material extraction energy (evolving over time).

II. Application : LCA Modeling of an energy transition scenario

1. Objective

Through this case study, the aim is to evaluate the Life Cycle Assessment (LCA) capacity to be used in order to make a complete (multi-criteria) environmental assessment of an energy transition scenario. However, the purpose of the study is limited to the evaluation of the mineral resources consumption required to guarantee an energy transition scenario. Water, energy and agro-resources are not considered in the analysis.

2. Scope of the study

For the purposes of this study, **the transition scenario used to carry out an LCA is the IEA ETP 2017 2DS scenario**. Indeed, this scenario is especially detailed with regards to the energy pathways and GHG emissions in the various sectors of activity.

However, the challenge lies in the fact that ETP scenario is constructed in order to ensure an energy loop between energy demand and available means of production (with a constraint on GHG emissions) for each year of the scenario. This is why it is necessary on a resource-consumption perspective to establish selection criteria in order to identify the sectors to study in the LCA, namely:

- Is the sector a resource-intensive one?
- Are the main resources consumed by the sector under pressure?
- Is the sector expected to experience technological evolutions which will change the mix of the consumed resources?
- Is the data concerning these resources available?

Based on these criteria, the following scope has been established, with several levels of integration in the analysis.

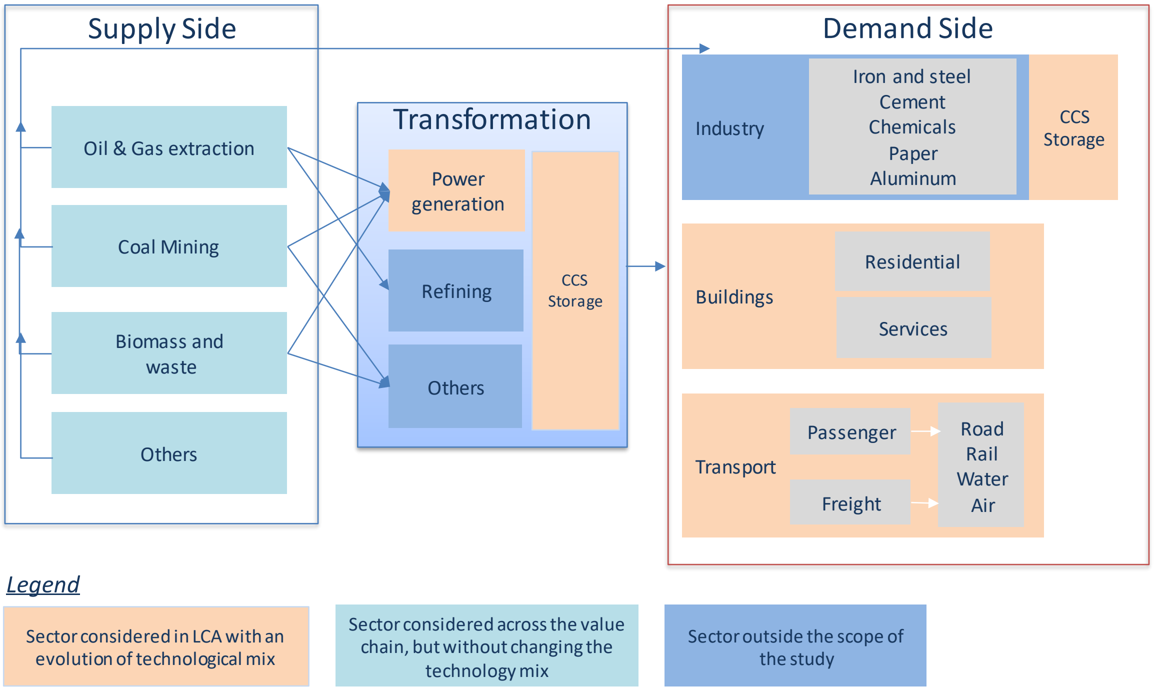


Figure 3 : Scope of the "test" LCA

The sectors considered in detail in the LCA were modeled by taking into account the evolutions of the technological mix, as detailed in the ETP scenario, and therefore new releases to the market (new energy production infrastructures, new vehicles, etc.):

- The “Power generation” sector: this includes the construction of the main power generation plants as detailed in the IEA scenario.
- The “Building” sector: this includes the construction of new buildings for secondary and tertiary sector.
- The “Transport” sector: this includes passengers and freight transport, in terms of vehicle fleet construction on all 4 modes (road, railway, air, maritime).
- The *CSS Storage* (Carbon Capture and Storage) is not a sector in its own right, yet involves the us pipes, which can impact material consumption.

The sectors considered in a simplified way were included in the analysis without modifying the existing technological mix (value chain of the Oil & Gas for instance). For transport infrastructures, only the depreciation of existing infrastructure was considered using the data already available in the ecoinvent database (railway for trains for instance).

3. Operating unit

For the purposes of this study, the operating unit definition refers to all the activity data of the scenario, within the scope defined above, for a given year. Thus, the evaluation is conducted for 4 distinct years:

- 2015
- 2025
- 2040
- 2060.

The operating unit could therefore be defined as follows: “implement the technical and operational capacities in the year 20XX in order to achieve the targets set by the IEA ETP 2017 2DS scenario at different time horizons”.

The main results will thereby represent of the material consumption and/or of the impact on resources on a given year.

4. Definition of the base-case of the ETP 2017 2DS scenario LCA

To be able to build the inventory and carry out such an LCA, it will first be necessary to extract the main elements of the ETP scenario, for each year studied, in terms of:

- Energy and electricity mix composition
- Activity data for each sector studied (number of vehicles in the fleet, number of m^2 of building constructed, etc…)
- Technological evolution (if available)

It is clear that not all data that can be extracted from the ETP scenario have the granularity required to conduct such a study. Thus, other data sources were mobilized to complement the ETP scenario elements.

Table 2 : Activity data identification obtained from the ETP 2017 scenario and other data sources

	Electricity Production	Transport	Building	Industry
Activity data available in the ETP scenario and used in this study	Power capacity (GW) and energy production (TWh) for each power generating means (PV, nuclear, onshore and offshore wind, etc…) Quantity of CO2 stored by CCS systems	For the road sector: fleet size for motor vehicles and road freight (millions), type of vehicle (gasoline, diesel, hybrid, electric, etc…) For the rail and air passengers sectors, the activity data is the number of	Number of new m^2 built per year (materials required for the energy refurbishment of the building are not taken into account)	CO2 quantities stored by the CSS systems

		passenger.km For rail freight, it is the number of t.km transported per year For the maritime sector, it is the number of t.km transported.		
Other data sources	Additional data from World Bank (quantity of materials per installed MW for CSP solar and nuclear)	For the air transport sector, additional data on the fleet evolution in terms of number of aircrafts are provided by an Airbus publication)	Ratios (materials kg/m^2) are obtained from Heeren et al. 2018	The estimate of the quantity of linear meters of pipeline per ton of CO2 captured is based on a Global CCS Institute study

A hypothesis on car weight reduction (substitution of steel by aluminium) was also considered.

5. Methodology for impact assessment

The methodology of abiotic resources depletion ADP (Guinée et al. 2002) is recommended by the methodological guide ILD 2011 and Product Environmental Footprint (PEF) as the midpoint method to be used to assess resources depletion (however it is classified at level II, i.e. “advised but requiring improvement”). It is based on two approaches:

- CML-IA baseline, abiotic depletion, ultimate reserve;
- CML-IA non baseline, abiotic depletion, reserve base.

As a reminder, the characterization factors of the CML method are calculated according to:

$$ADP_{i,geologic\ stock} = \frac{extraction\ rate_i}{geologic\ stock^2} * \frac{geologic\ stock\ antimony^2}{extraction\ rate\ antimony}$$

One of the major limitations of these indicators is their "fixed in time" aspect. Indeed, the characterization factors for the two CML methodologies were constructed from extraction and reserve data from the 2000s, which does not seem suitable for evaluating a transition scenario to 2060.

Thus, one of the ideas pursued in this study is the construction of characterization factors based on Schneider's AADP method (Schneider, Berger, & Finkbeiner, 2011). Indeed, this author underlines the importance of studying abiotic resources for the role they play in society rather than their natural availability as such. As a result, 3 existing and applicable methods were used, in this project and the method that we believe is the most complete, Anthropogenic stock-extended Abiotic Depletion Potential (AADP), was modified to see the effects of these modifications on the results. The three methods used are:

- CML-IA baseline method, abiotic depletion, ultimate reserve;
- CML-IA non baseline method, abiotic depletion, reserve base;
- AADP Schneider 2015 method.

An update of the method suggested by Schneider was carried out to assess the long-term availability of resources. The proportion of abiotic resources finally available for human extraction has been deducted from the amount of elements available in the earth's crust. An update of the characterization factors is proposed in this study, based on extraction rates and anthropogenic stock levels, recalculated and adapted to each time horizon of the scenario. The new characterization factor for a resource is therefore calculated by the following formula:

$$\text{AADP}_{i,\text{ ultimately extractable reserves}} = \frac{\text{extraction rate } i}{(\text{extractable geologic stock } i + \text{anthropogenic stock } i)^2} \times \frac{(\text{extractable geologic stock antimony} + \text{anthropogenic stock antimony})^2}{\text{extraction rate antimony}}$$

6. Results the LCA test performed

6.1 Comparison of the scope of the study with USGS data

A first consistency analysis of the results was carried out in this study by comparing the data modelled in 2015 with the ETP scenario and the extraction data from the US Geological Survey (USGS, 2015).

This first comparison makes it possible to assess the extent to which LCA can be used to account for resource consumption in a given reference year, i.e. 2015. Indeed, the inventories in the LCA databases make it possible to estimate the amount of metal contained in the different ores which is extracted for each process from the ecoinvent database. The comparison can therefore be made on the extraction data proposed by the USGS.

Since not all sectors of activity were modelled in the LCA, an estimate of the share of global quantities involved in the three sectors modelled (energy, transport, building) was made. This estimate of the quantities of materials allocated to our three study sectors was only made on a selection of main raw materials.

Table 3 : Comparative assessment of resource consumption between the LCA study and USGS 2015 data

	World consumption data (USGS, 2015, Mt)	Share of the sectors studied in LCA in global consumption (USGS, 2015, %)	Share of the sectors studied in the LCA in global consumption (USGS, 2015, Mt)	Consumption data according to LCA (2015, Mt)	Share of LCA flows in the studied sectors (%)
Aluminium	58.3	65%	37.9	**17.9**	**47%**
Copper	18.7	60%	11.2	**8.1**	**72%**
Iron ore	3320	68%	2258	**397.7**	**18%**
Lithium	0.033	25%	0.008	**0.009**	**117%**
Zinc	13.4	61%	8.2	**1.1**	**14%**
Nickel	2.5	68%	1.7	**5.1**	**298%**
Lead	4.7	80%	3.8	**0.7**	**18%**

Flow modelling by the "test" LCA seems to correspond relatively closely to USGS quantities for copper and lithium, but this is not the case for other mineral resources. Some explanations can be provided:

- Aluminium: USGS data are more important than the LCA modeled data because, in this case, USGS provides metal consumption data (primary and secondary) and not the amount of primary aluminum extracted from bauxite. It is therefore consistent that the data from the LCA should be significantly lower than the USGS value.
- Iron ore: the share of iron (and steel) in construction and infrastructure is significant (around 50% of world consumption). Since the additional infrastructure (particularly rail infrastructure) was not modelled in the test LCA, this is one of the factors that explains the low coverage rate of the test LCA. In addition, an overestimation of the actual share of recycled steel in the

various end markets could also explain the difference between the result of the LCA test modelling and USGS statistics.

- Nickel: the trend is completely different for this element. It appears that LCA modelling evaluates a much higher primary metal consumption data than that provided by the USGS. This could perhaps be partly explained by the fact that in the ecoinvent database, the use of copper leads to the extraction of nickel as an extraction by-product, which leads to double counting.

It should be noted that LCA test modelling often takes into account through inventories a share of recycled metal, which, if different from that actually observed on the market, can also be a source of discrepancy between the data extracted from the USGS and the modelling by the LCA test.

6.2 Evolution of consumption in 2025, 2040 and 2060

The second assessment carried out consists in compiling the raw material requirements for the implementation of the ETP scenario, for each year considered in the scenario. Thus, the modelling of the evolution of the flows of materials consumed by 2025, 2040 and 2060 compared to the 2015 reference year highlights several groups of raw materials:

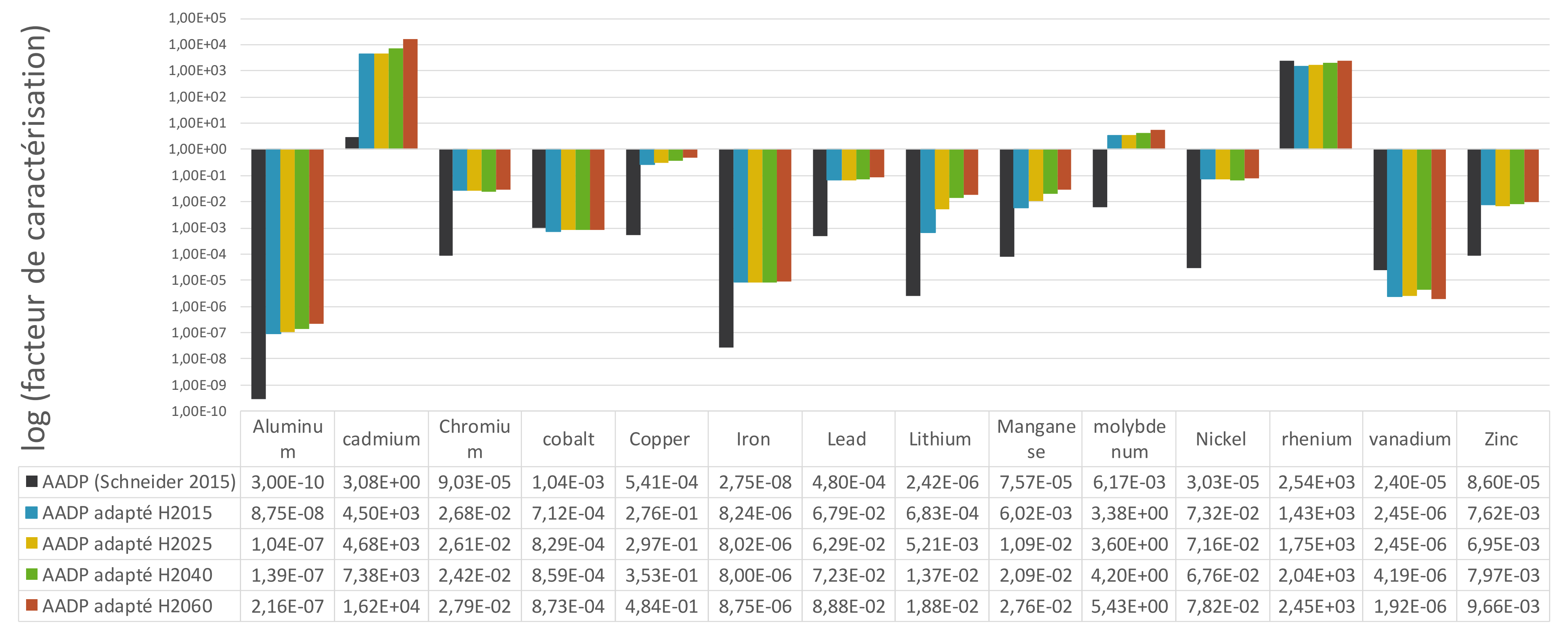
- Lithium and neodymium, for which demand is exploding: 27 times more lithium demand in 2060 than in 2015, 309 times more neodymium;
- Manganese, cobalt and gold, for which demand increases very strongly between 2015 and 2060 (factor 3.2 for manganese to factor 4.8 for cobalt);
- Aluminium, copper, silver and molybdenum, for which demand is growing significantly (between 0 and 100% by 2060);
- Iron, chromium and nickel for which demand decreases between 2015 and 2060. This counter-intuitive result is explained by the long-term decline in demand for building construction, and therefore in the consumption of associated steel and its various alloys.

In general, a sharp increase in raw material requirements was observed overall over the period studied. For the "commonly used metals" group, consumption is on the rise throughout the scenario, except for iron. For the group of "minor metals" and precious metals, the most significant change in consumption concerns neodymium, with 37,000 tons in 2060 compared to 112 tons in 2015.

6.3 Impact of the 2017 ETP scenario on resource depletion (2DS)

6.4.1. Analysis of characterization factors (CF)

The graph below shows the characterization factors with AADP methods (base and update). This graph is produced with a logarithmic scale ($\log_{10}$) in order to allow a better visualization.



	Aluminum	cadmium	Chromium	cobalt	Copper	Iron	Lead	Lithium	Manganese	molybdenum	Nickel	rhenium	vanadium	Zinc
■ AADP (Schneider 2015)	3,00E-10	3,08E+00	9,03E-05	1,04E-03	5,41E-04	2,75E-08	4,80E-04	2,42E-06	7,57E-05	6,17E-03	3,03E-05	2,54E+03	2,40E-05	8,60E-05
🟦 AADP adapté H2015	8,75E-08	4,50E+03	2,68E-02	7,12E-04	2,76E-01	8,24E-06	6,79E-02	6,83E-04	6,02E-03	3,38E+00	7,32E-02	1,43E+03	2,45E-06	7,62E-03
🟨 AADP adapté H2025	1,04E-07	4,68E+03	2,61E-02	8,29E-04	2,97E-01	8,02E-06	6,29E-02	5,21E-03	1,09E-02	3,60E+00	7,16E-02	1,75E+03	2,45E-06	6,95E-03
🟩 AADP adapté H2040	1,39E-07	7,38E+03	2,42E-02	8,59E-04	3,53E-01	8,00E-06	7,23E-02	1,37E-02	2,09E-02	4,20E+00	6,76E-02	2,04E+03	4,19E-06	7,97E-03
🟥 AADP adapté H2060	2,16E-07	1,62E+04	2,79E-02	8,73E-04	4,84E-01	8,75E-06	8,88E-02	1,88E-02	2,76E-02	5,43E+00	7,82E-02	2,45E+03	1,92E-06	9,66E-03

Figure 4 : Comparison of the original characterization factor (Schneider et al. 2015) compared to the factors updated in this study

The comparison between the characterization factors (CF) published by Schneider compared to that of the CF updated at different time horizons shows that:

- The value of Schneider's CF is lower than that recalculated for 11 of the 14 resources,
- The Schneider CF value is higher than those recalculated for 3 resources (cobalt, rhenium and vanadium).

These trends are explained by the fact that the extraction rates used in the updated calculations are higher or lower than those used by Schneider from the reports published by the USGS in 2013 and 2014[1].

Thus, updating the characterization factors of the Schneider method has a significant impact on the values of the characterization factors, positively or negatively depending on the resources.

6.4.2. Analysis of the comparative results of the scenarios according to the methods

The figure below presents the impact results on resource depletion with the 4 methods used for each of the 4 time horizons (logarithmic scale $\log_{10}$).

Figure 5 : Analysis of the comparative results of the scenarios according to the methods

The impact on resources tends to increase from 2015 to 2060 with all methods. The scenario analysis with the CML baseline - ultimate reserve method shows a constant upward trend in the impact on the different time horizons, while for the other 3 methods there is a slight decrease in the impact between 2015 and 2025 and then a constant increase until 2060. The updated AADP analysis presents results that are 3 to 4 orders of magnitude higher than the results of the other 3 methods.

Tableau 4 : Rate of change in impacts on different time horizons

	Rate of change in results 2015→ 2025	Rate of change in results 2025→2040	Rate of change in results 2040→2060
ADP CML baseline: ultimate reserve (%)	**+6%**	**+33%**	**+36%**
ADP CML non baseline : reserve base (%)	**-9%**	**+20%**	**+23%**
AADP Schneider et al. 2015 (%)	**-12%**	**+15%**	**+18%**
AADP updated (%)	**-10%**	**+79%**	**+155%**

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[1] Mineral commodity summaries. U.S. Geological Survey, Department of the Interior, Reston

In summary, the following elements concerning the impact characterization methodology can be highlighted by the analysis conducted in this study, namely:

- The results obtained with the 4 methods studied present an almost invariant resource contribution profile.
- With the AADP Schneider et al. 2015 and updated AADP methods, cadmium represents the vast majority of the impact on the 4 time horizons (its characterization factor is the highest on the different time horizons although its extraction rate does not represent more than 0.006% of the resources extracted on the 4 time horizons). It is therefore questionable whether the high value of the cadmium characterization factor is consistent.
- The updated AADP method has the benefit of changing the characterization factors according to the evolution of resources, which is an interesting methodological element if we look at distant and prospective time horizons. This update of the characterization factors does not seem to modify the contribution profiles to the impact (cadmium remains the majority contributor), but it modifies the absolute value of the impact results.
- The ADP reserve base method does not seem suitable for assessing resource scarcity on remote time horizon scenarios (estimated reserves depend on many factors that can change in a very short period of time).

In addition, the following lessons can be drawn from this first "test" LCA conducted on the ETP 2DS transition scenario:

- Each time horizon was constructed from data collected in the IEA ETP 2017 scenario and supplemented by various data sources, but inventory construction remains a challenge.
- The modelling was carried out in LCA software to identify whether or not a material balance can be established. But it seemed impractical to release all the results because this type of software is not very suitable for carrying out Material Flow Analysis (MFA) studies. Post-output work on the results is mandatory and time-consuming in order to be able to interpret the raw results.
- Carrying out an energy transition scenario LCA is a time-consuming task. Data collection, analysis and processing, search for missing data, scenario building, detection of double counting, solicitation of experts to validate hypotheses, etc.
- The LCA made it possible to show the consequences of taking into account the evolution of resource availability over time by the updated Schneider et al. 2015 method.
- The robustness of the LCA results of the energy transition scenarios depends in part on the choice of inventory data. Thus, the assessment of potential environmental impacts generated by these scenarios is based on a fundamental uncertainty: the modelling of immature or non-existent technologies that will be used in several decades.

Therefore, it appears from this study that conducting an LCA is possible. However, the results obtained are subject to significant uncertainties. These uncertainties could not be estimated (difficulty of quantification) since the hypotheses may concern prospective temporal and spatial perimeters. It is a real challenge to evaluate the quality of prospective data. This study highlights the need for further developments on the 4 stages of LCA in order to be able to claim to assess the environmental aspect of energy transition scenarios by LCA in a more robust way.

The diagram below presents three possible approaches to improve the assessment of an energy transition scenario by LCA.

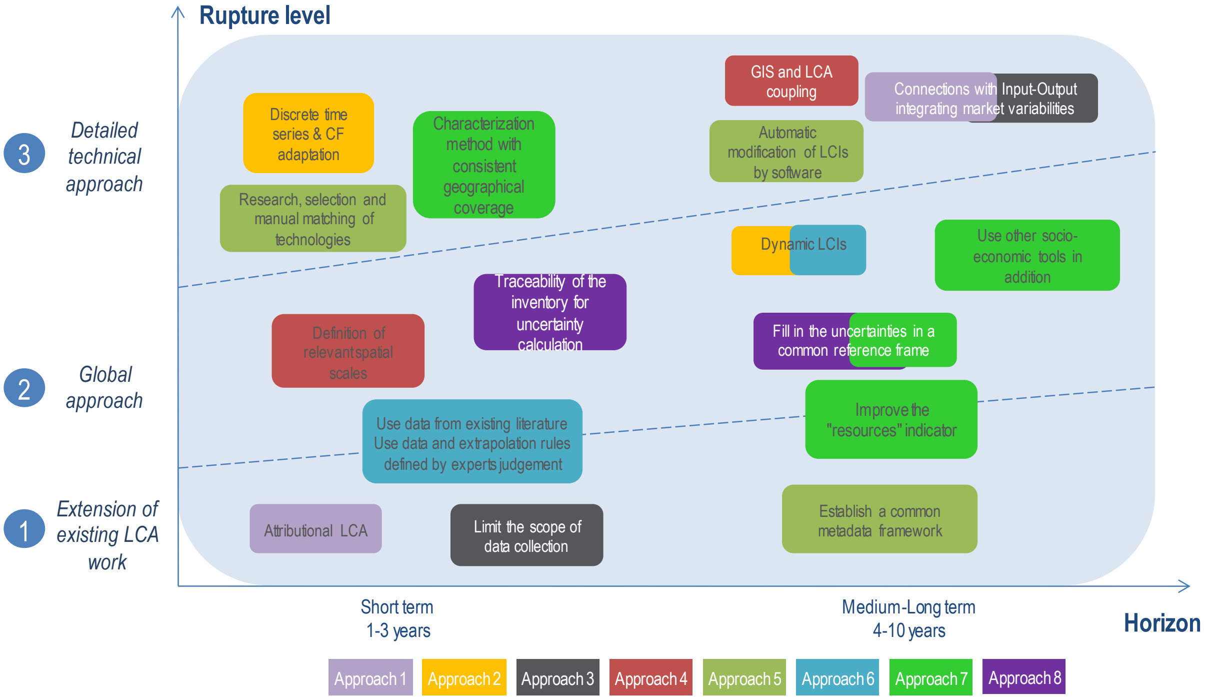

Figure 6 : Short- and medium-term research options for improving the LCA assessment of an energy transition scenario

Conclusions

The International Energy Agency's *Energy Technology Perspectives 2017 (2DS)* scenario is an international benchmark because it takes into account in detail the emissions of different sectors of activity. In particular, it provides for a 70% reduction in annual CO_2 emissions from the energy sector compared to the current level by 2060. However, it seems difficult to grasp the problem of resource depletion, particularly in this context of strong development of renewable energies. The main issues for assessing the risks of exhaustion focus on:

- The assessment of the need for resources, whether for the sectors affected by transitions, or for other sectors of activity;
- Evaluation of levers for reducing virgin material demand (recycling, substitutability);
- Identification of the exhaustion of deposits.

Thus, it is now difficult to estimate whether there is a real risk of resource depletion in the coming years, despite a growing literature on the subject. Studies identify series of ores for which tensions appear to be predictable by 2050, but these ores differ from one study to another. This is why it appears that Life Cycle Assessment (LCA), as a multi-criteria methodology, has a key role to play in assessing the environmental impacts of transition scenarios, including resource depletion. LCA makes it possible to precisely, extensively and quantify the transition scenarios and the material and energy flows required for this transition, and thus to make an important contribution to the debate on the issue of limited resources.

However, the application of LCA to the 2017 ETP scenario has highlighted various obstacles to the use of LCA in this prospective transition scenario context, both methodological (attributional-based or consequential-based LCA?), relating to the availability of inventory data (technology evolution by 2060?) and to the characterization of environmental impacts (reliability of indicators of resource depletion available in a prospective context?).

To conclude, although the LCA now allows for an initial quantitative assessment of resource needs for the transition and a characterization of the impacts regarding their depletion, various additional studies will be required to make this type of analysis more reliable.

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