The material impacts of an energy transition based on sufficiency, efficiency, and renewables

Emmanuel Rauzier
Association négaWatt
BP 16280 Alixan
F-26958 Valence Cedex 9
France
e.rauzier@institut-negawatt.com

Edouard Toulouse
Association négaWatt
BP 16280 Alixan
F-26958 Valence Cedex 9
France
edouard.toulouse@negawatt.org

Keywords

materials, circular economy, efficiency, sufficiency, industry, resources, Negawatt, transition

Abstract

For two decades now, the négaWatt Association has published and updated a comprehensive energy transition scenario for France showing how the country could switch to a 100 % renewable supply with the support of energy efficiency and sufficiency to curb demand.

Recurrent questions were often heard about the material impacts of such a scenario, e.g. on the risks of potential depletions and how sufficiency and circular economy principles could be applied to material resources. To answer such interrogations, the scenario experts have undertaken a considerable modelling work and developed a calculation tool called 'négaMat'.

This paper describes the objectives and approach of négaMat. It specifies in details its methodological step and illustrates them by results obtained through its application to the French négaWatt scenario.

It shows for instance that buildings and civil works represent the largest tonnage of material use, and moderating the need for new buildings would have a substantial impact. Sufficiency could also reduce the consumption of other goods (paper, electronics, vehicles…). The calculation module reveals how these drops in consumption could be offset by smart relocation of some manufacturing sectors in the country, leading to a relative stabilisation of the total industrial activity.

NégaMat can also provide insights on which material resources could be put under pressure by energy transition. Iron is not really an issue, but copper deserves special attention in the development of a 100 % renewable grid. Electric mobility is also a source of concern, as a one-to-one electrification of current vehicles would lead to significant difficulties with respect to lithium. Only a scenario in the négaWatt spirit with sufficiency efforts (less distance travelled, substantial modal shift, higher carpooling and a mix of sustainable motorisations) could mitigate the risks on the resource.

Introduction

Since 2001, the NégaWatt Association has developed a systemic energy transition scenario for France that would achieve a 100 % renewable energy supply by 2050[1]. This scenario is based on sufficiency, efficiency and renewables. Sufficiency is about reducing our needs for energy-consuming services and goods, while efficiency is more well-known and consists in reducing the energy used for providing a certain service. During the conception of the model supporting the scenario, the following questions had arisen with respect to the industrial sector:

- Is it possible to forecast the consumption of goods and materials according to a predicted quantity demand and not a supposed market value?
- How are changes in the consumption of goods related with the flows of materials they are made of?
- What are the links between local production and consumption including imported products?

1. NégaWatt association. https://negawatt.org/en

- How to calculate precisely the impact on goods and material consumption of an energy transition (based on sufficiency, circular economy and new technologies)?

To answer this type of questions, in the latest update of the négaWatt scenario (négaWatt 2021) the industrial calculation tool has been substantially reinforced and split into two parts. The first prospective tool named "négaMat" assesses the quantities of goods and materials that are necessary and consumed in the scenario. The second tool evaluates improvements in industrial energy intensity and the possible emergence of new technologies. These two tools can run together to provide the industrial energy consumption and GHG emissions resulting from the scenario implementation. The first added-value of this approach is to clearly distinguish the contribution of circular economy and sufficiency aspects from that of technical and industrial efficiency. A second added-value: the négaMat tool is able to assess the material footprint of the scenario and the influence on the needs for raw material extraction.

This paper provides an overview of the négaMat tool, starting from a methodological description and then providing insights and examples of the main benefits and outcomes when it is applied to the French négaWatt scenario.

Model description

Most prospective models covering materials and goods rely on economic assessments of the increase in value of goods and forecasts of trends on materials which are more or less correlated. For instance, the IEA's SDS[2] models energy demand in industry on the basis of changes in GDP and changes in added-value for a given sector (IEA 2021a).

There is an increasing number of modelling exercises investigating specifically the future needs for materials, including in the context of an energy transition (IEA 2021b, Takuma et al 2019). Others investigate specific sectors, such as construction and transportation (Pauliuk et al 2021). Most of them are global but some are country-specific, for instance for France (Baylot et al 2019).

The négaMat tool has been developed internally by experts of the négaWatt Association, based on an initial cooperation programme with the French energy agency (ADEME 2020). It has similar objectives as the aforementioned models, but also specificities:

- The model investigates a particularly wide range of sectors, listed in Figure 2. Thus, it may be used for a comprehensive assessment of the material aspects of a systemic scenario. It is also possible to distinguish between sectors, e.g. new mobility, energy supply system, etc.
- Its current version includes a mapping to the reference year, prospective assumptions on an annual basis, and a module for calculating and outputting results. The input data for the mapping includes production, import, export, and consumption mass flows for materials and even for the main consumer and industrial goods. The calculation module can account for assumptions on sufficiency, circular economy, recycling rates, and the evolution of I/E[3] rates.
- The prospective assumptions and the calculation module are clearly separated, so that the tool may potentially be run and give results for differentiated scenarios. So far, it has been used for the 2021 version of the négaWatt scenario (négaWatt 2021), as well as for a series of climate neutrality scenarios prepared by ADEME (ADEME 2021). The tool is designed to work with different types of scenarios, countries, or regions such as Europe for example, provided statistical data is available.

Basically, the tool investigates the chains connecting final good consumption to raw material needs upstream. It has been designed to evaluate physical flows (tons/year) of production and consumption of materials, but also of goods (irrespective of their market value). Results at each stage for different products are described in figure 1.

In the model, goods and materials are correlated by a material balance according to the diagram in Figure 1. In practice, this is implemented through nested matrices between raw materials / basic materials / processed materials/consumer and equipment goods. For example, the tonnage of cars produced in a certain year is related to the tonnages of the constituent materials (steel, glass, plastics, etc.). And the plastics themselves are related to the tonnages of olefins or other chemicals, themselves related to the oil from which they are derived.

The négaMat approach follows a similar logic to the overall approach of the négaWatt Association, that is to look at energy and material needs in a bottom-up perspective: instead of deriving them from macro indicators such as GDP, it goes the other way round by first questioning our needs for energy and material services and how these could be systematically reduced and optimised through sufficiency and different societal set-up. It requires a thorough and detailed investigation of all sectors and services.

The physical flows of materials are analysed upstream "from the cradle to the grave", i.e. from the extraction of resources to the final product available in shops and then to waste and its treatment. These flows are traced backwards from the finished products to the resource extraction and then to the waste/recycling stage. This is reflected in the direction of the arrows in Figure 1.

These consecutive steps will now be further specified and illustrated by concrete examples from the négaMat implementation.

STEP 1: CONSUMPTION OF GOODS

Consumer goods are the final products offered for sale to satisfy the needs of citizens or the community. Equipment goods are products required for manufacturing, such as machine tools, construction equipment, to which we should add fertilisers and packaging. These goods (which we call 'CEGs'[4]) can be divided into 9 categories, which we have subdivided into 128 subgroups as shown in Figure 2. For example, electronics include computers, communication devices, consumer electronics, and

2. Sustainable Development Scenario

3. Import/export

4. Consumption and Equipment Goods

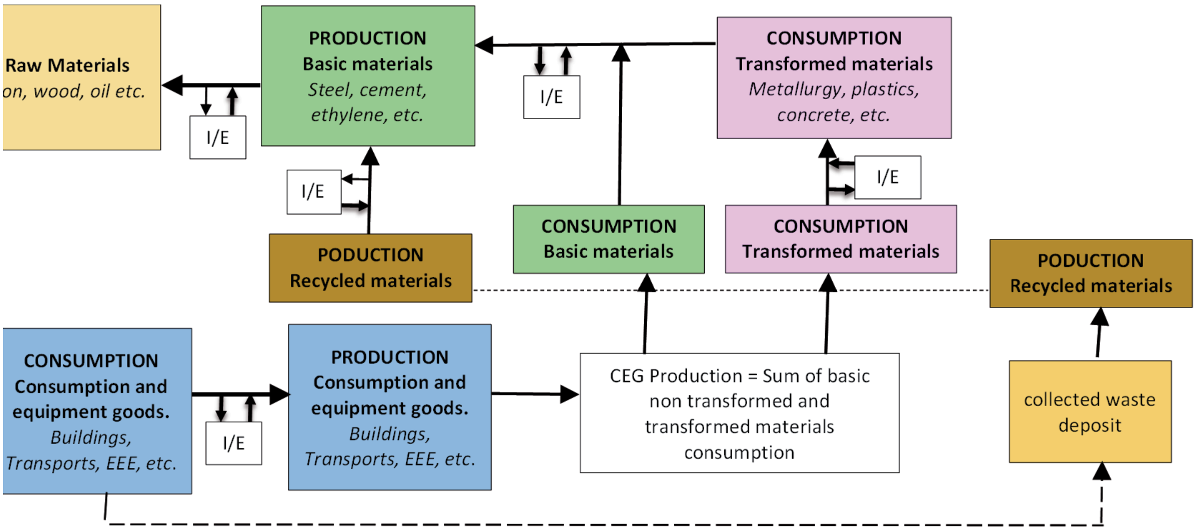

Figure 1. Synoptic of the relationships between consumption and production of goods and materials; I/E stands for Imports/Exports. The dotted line means that waste deposit is not related to present but to past consumption (see step 4).

Table 1. The different groups and number of sub-groups of consumer and equipment goods, and the levers for sufficiency and circular economy.

	Size suffic.	Use suffic.	Share suffic.	Reuse	Repair	Recycle	nb Sub Sectors
FOOD AND BEVERAGE	YES	YES	NO	NO	NO	NO	8
PAPER	YES	YES	NO	NO	NO	YES	3
MECHANICAL EEE	YES	YES	YES	YES	YES	YES	15
TEXTILE OTHERS	YES	NO	Seldom	YES	YES	YES	14
PACKAGING	YES	YES	NO	YES	Seldom	YES	11
TRANSPORTS	YES	YES	YES	YES	YES	YES	15
FINE CHEMISTRY	YES	YES	NO	NO	NO	NO	11
BUILDINGS CIVIL ENG.	YES	YES	YES	YES	YES	YES	19
ENERGY NETWORKS	NO	NO	NO	NO	YES	YES	32
GLOBAL							128

professional equipment. However, active and passive components and boards, as well as batteries, are not included in this list. We consider those as intermediate products used in the manufacturing of various items (cars, networks, etc.).

The evolution of CEG consumption depends on three main criteria:

- Sufficiency, one of the three pillars of the négaWatt approach (négaWatt 2018), which consists in creating the conditions to moderate our need for energy-intensive and material-intensive services. It can be dimensional sufficiency (e.g. optimising the size of a refrigerator to our real needs), usage sufficiency (e.g. reducing the frequency of use of appliances), or collaborative sufficiency (e.g. increasing carpooling).
- The reuse of products which exist for the second-hand market (e.g. vehicles). It can be increased for packaging through deposit systems for instance.
- The lifetime of goods, which relates to repairability, availability of spare parts, and appropriate after-sales services.

The relevance of these criteria according to each CEG group is summarised in table 1, to which we added recycling, another important pillar of the circular economy (that we will discuss later).

As an example, Figure 2 below shows the results of applying négaMat to the French négaWatt scenario and presents the consumption of goods in Mt in 2014 and by 2050. Buildings and public works is the most important tonnage, with a decrease of 36 % between 2014 and 2050. Due to demographics and a stabilisation of the number of people per household in the scenario, it becomes less necessary to build as many new dwellings as today. The already very dense road network no longer requires new roads but (a less material-intensive) maintenance. With nearly 100 Mt, food is in second place and although average diets substantially change in the Afterres scenario that inspired négaWatt (Solagro 2016), the overall quantities remain similar.

We can compare these results to other studies. Building and transport evolutions have been analysed in Paliuk et al 2021, in which they looked at a scenario with less floor space per person, product lifetime extension, reuse, car sharing and higher scrap recovery. Despite a very different scope (global for Paliuk et al and country-specific for négaMat), a similar large decrease is observed between 2015 and 2050 for cement (-63 % for both scenarios) and steel (-62 % for Paliuk et al, and -48 % for négaWatt). In Paliuk et al, wood decreases by -11 % but only by -3 % in négaWatt, in which biomass use is higher. However, results for alumina and copper are largely diverging because mobility assumptions are very different in both studies, notably concerning average car size and travelled distances (the geographical scope difference probably plays a key role here).

Under the négaWatt scenario assumptions, other flows of goods and materials are massively reduced, except for energy supply and networks, in line with the 100 % renewable target. Paper decreases by 38 % by 2050 (replaced by digital tools). Mechanics and EEEs[5] decrease by 22 % despite an increased use of digital services, offset by more durable devices (which integrate more functions, are smaller, and eventually more repairable). The mass of vehicles used for transport is decreasing by 44 %, mainly due to reduced road mobility (-28 %) in favour of public transport, and in smaller (-30 %) and more durable vehicles (+28 %). The occupancy rate plays an important role, as it is supposed to increase from 1.69 to 2.03 by 2050. Except nitrogenous fertilisers, which decrease by 40 %, other products show smaller variations.

The energy transition as proposed by négaWatt requires more materials in some sectors (due to changes in energy carriers and sources, increased storage, technological improvements, etc.), but this is compensated overall by decreases in other sectors thanks to sufficiency and durability efforts.

STEP 2: FROM CONSUMPTION TO PRODUCTION

The production of goods (P) in a given year is linked to the consumption (C), international trade flows (exports E and imports I) and stocks (S) through the following formula: $C = P + I - E - S$. Statistical data was generally available in France for the starting year of our tool for most goods. As regards future assumptions, a range of hypothesis is required regarding the P/C ratio. The tool allows to set such assumptions for 58 sectors of final goods, to which we added 137 sectors of basic, intermediate, and recycled materials. For each sector, a P/C ratio below 1 indicates a net import in the country, otherwise a net export.

In a physical flow model such as négaMat, it is necessary to anticipate the evolution of international trade. The higher or lower relocation of the production of goods influences the consumption of incoming materials and all the downstream industry (which is generally energy-intensive and a major source of carbon emissions). How to anticipate the trends in relocation? The answer is largely political, as it is linked to financial, employment and incentive measures that could be put in place. Such measures are particularly debated in many countries in the context of post-COVID recovery plans.

For instance, in France a recent report of the High Commission for Planning (HCP 2021) highlights that for several years the French industry has declined in favour of imports (which worsens the country trade balance). Various assumptions are possible; the négaWatt scenario supposes a certain amount of targeted relocation in the future.

Figure 2 shows the evolution of production and consumption between 2014 and 2050 when applying négaMat to the négaWatt scenario and the main groups of goods. As the building and public work sector cannot be moved, its P/C ratio remains at 1. For the food and beverage sector, P/C is close to 1 and this should not change much by 2050.

At present, the P/C ratio is particularly low for the energy system (0.49), as wind turbines and photovoltaic panels are mostly imported from outside France. The mechanical engineering and EEE[6] sectors (P/C of 0.62) and textiles (P/C of 0.37) are also in a large balance deficit. By 2050, it is interesting to note that the situation could be substantially rebalanced through a progressive relocation of renewable energy systems. In addition, sufficiency and circular economy could reduce overall consumption needs by 22 %, but this reduction would be offset by relocation of some sectors. In the end, the bottom-up assumptions of the négaWatt scenario translate into a relative stabilisation of the level of industrial production in France by 2050. It reveals that a drop in energy and material consumption through sufficiency and efficiency does not necessarily mean an economic or industrial recession.

STEP 3: MATERIAL CHAINS

As figure 1 showed, the production of goods is related to the consumption of materials, either basic or processed (or intermediate). Basic materials may be grouped in five classes:

- biomass materials: wood and crop products for the food industry,
- metals: steel, aluminium, copper, Pb, Zn, Ni, Sn, Cr, Mn, cobalt and precious metals,
- silica and lithium,
- mineral products: earth, sand, aggregates, clinker, plaster, lime,
- chemical bases: ammonia, chlorine, soda, olefins, aromatics, and others.

Some basic materials are derived directly from raw materials as they are used as such for intermediate products (e.g. timber, sand for concrete, etc.). From the basic materials to the CEGs, the chains are more or less complex:

- Examples of second-order chains: direct steel → railway; aggregates → construction,
- Examples of third-order chains: clinker → cement → concrete → construction; ethylene + benzene → styrene → polystyrene → packaging,
- Examples of a chain of order five: refined copper → copper alloy → electronic component → electronic board → computer.

The material is not always part of the composition of a good. In addition to losses, it is sometimes just used as a catalyst for an industrial process. For example, soda ash is needed to produce Kraft paper, oxygen for the steel industry, etc.

The composition of a CEG may change over time due to weight reduction or material substitution. In the négaMat tool, this potential could not be taken into account for a number of goods due to methodological limits (e.g. furniture or paints), but is considered for the most energy-intensive sectors. For ex-

5. Electrical and electronic equipment

6. Electric and electronic equipment

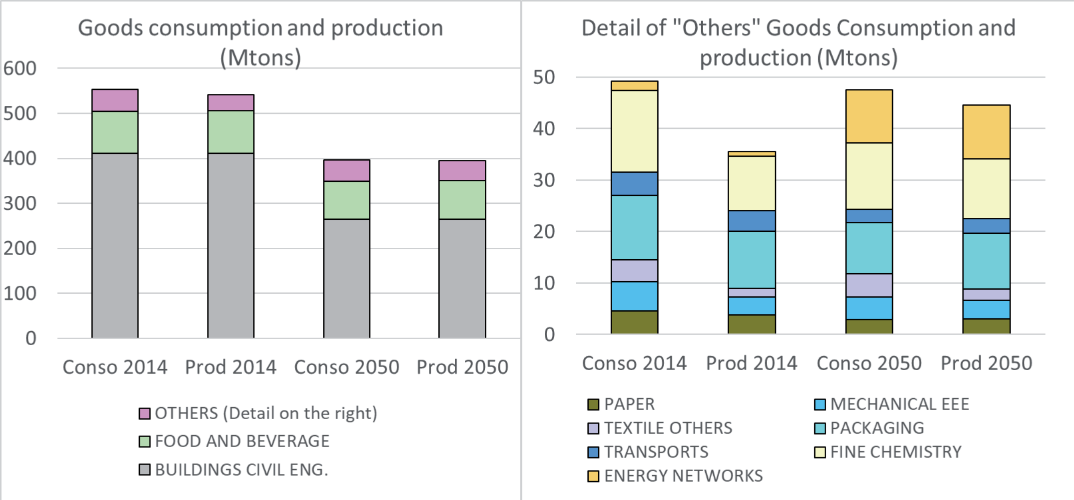

Figure 2. Evolution of the consumption and production of goods in the négaWatt scenario (négaMat output).

ample, each type of packaging is treated separately, allowing for substitution from one to the other. Nitrogen, phosphate, potassium, or natural fertilisers are treated separately, which also allows for substitution. Concerning the building sector, specific assumptions are made regarding the market shares of wood or concrete in structures, wood, aluminium or PVC in joinery, polystyrene, glass wool or bio-based insulation, etc. For transport, the mass and composition of each type of vehicles (thermal, electric or hybrid) may be adjusted over time in the tool.

STEP 4: WASTE AND RECYCLED RAW MATERIALS

When assessing materials, it is necessary to consider their origin: primary or recycled. The négaMat tool has an elaborated waste and recycling module that works as follows:

1. First, for each CEG the waste stream is assessed. Each CEG is assigned a life span ("DV"), e.g. less than one year for foodstuff or packaging, and around 15 years for cars. The mass of end-of-life CEG in a given year x corresponds to the consumption of this good in year x-DV. For this purpose, the history of consumption since 2000 needs to be traced. Only the building sector escapes this rule because it is illusory to evaluate the average lifetime of a building: a specific calculation considers trends of destruction in the past to anticipate that of the future.
2. The waste is then directed to agricultural recovery, incineration, or recycling with appropriate directional rates. The remainder is considered to be landfilled or lost. The recycling rate at this step is called the collection rate and corresponds to the departure to a sorting facility.
3. In the sorting facility and for each good, the materials are not treated equally: steel is generally very well recovered, while plastics much less. For five main groups (construction, transport, packaging, batteries and others), we have set a material recovery rate for each material. Material that is not recovered is ultimately considered lost or buried.
4. The recycled raw material (RRM) is then subject to the international import/export market, and enters production with an incorporation rate defined as the ratio RRPM / total material produced, also called EOL-RIR[7] (JRC 2018).

The incorporation rate thus calculated from waste deposit is not automatically the one that will be used in the modelling. Technical constraints also need to be taken into account. For example, because of fibre breakdown, the maximum rate of recycled paper cannot exceed 80 %. For recycled steel, the rate could be not as high as forecasted for two reasons: the availability of the industrial tool (EAF[8]) and the steel quality that doesn't allow some uses (e.g. worst resistance for steel sheets). Two main cases may then arise:

- The incorporation rate calculated by the waste deposit (which may even be above 100 %) is sufficient but higher than the technical rate. The latter value is used.
- The incorporation rate calculated by the waste deposit is lower than the technical rate, and it is this waste-related rate that is used. This is particularly true in a growth area such as lithium batteries. Even if considerable progress is expected on the recyclability of lithium, with an average growth rate of 6 %[9] and a battery life of 7 years, the lithium deposit from end-of-life batteries may only reach 67 % of future production needs.

Table 2 illustrates these different steps with the example of plastics in France in 2014 and their evolution in 2050 under the négaWatt scenario. It can be noticed that in 2014, for mechanical and electrical appliances as well as transport equipment, collection for recycling for the whole sector is rather good. This collection is lower for construction (46 %) and miscellaneous items (18 %). The total amount of what is collected and what is going to be sorted corresponds to about 110 Mt, and plastics is only a small fraction of this, i.e. 3.104 Mt, the potential plastic waste stream to be recovered.

7. End of Life Input Rate
8. Electric Arc Furnace
9. This is the average growth rate of lithium consumption between 2022 and 2037 in the négaWatt scenario

Table 2. Example of plastics contained in end-of-life goods, collection rate to sorting centres, recovery rate, and incorporation rate in manufacturing in the négaWatt scenario.

Mt 2014	Global waste	Collect rate	Collected for recycl.	Embodied Plastics	Recover rate	RPM
SUM				3,104		0,712
Mechanicals EEE	5,215	72%	3,773	0,584	18%	0,104
Others	3,849	18%	0,682	0,225	14%	0,032
Packaging	2,060	35%	0,711	0,695	52%	0,363
Transports	4,954	95%	4,706	0,450	12%	0,055
Buildings	222,327	46%	102,24	1,150	14%	0,158

	RPM
SUM	0,712
Export	0,339
Prod RPM	0,373
Prod plastics	5,476
Incorpo RPM	7%

Mt 2050	Global waste	Collect rate	Collected for recycl.	Embodied Plastics	Recover rate	RPM
SUM				3,956		2,606
Mechanicals EEE	4,792	87%	4,167	0,650	57%	0,372
Others	4,485	80%	3,588	1,353	55%	0,741
Packaging	1,515	80%	1,212	1,186	85%	1,010
Transports	2,746	100%	2,746	0,265	67%	0,176
Buildings	109,950	57%	62,78	0,503	61%	0,306

SUM	2,606
Export	0,244
Prod RPM	2,362
Prod plastics	5,050
Incorpo RPM	47%

But recovery rates of plastics in sorting facilities are currently low (between 12 and 18 %), except for packaging (52 %). The production of RPM is then 0.712 Mt, still four times less than the potential plastic waste deposit. At the next step, about half of these RPM are exported and only 0.373 Mt are used in manufacturing, which leads to an average incorporation rate of only 7 %.

This poor performance improves by 2050, as through dedicated policies and efforts the plastic waste stream is assumed to reach almost 4 Mt to end up in production at 47 %, six times higher than in 2014.

STEP 5: RAW MATERIAL RESOURCES

At the final stage of the négaMat approach stand raw materials, which are grouped into four main categories according to the EUROSTAT MFA[10] classification (EUROSTAT 2018): biomass, metals, non-metallic minerals, and fossil fuels. Each category is divided into subclasses.

What is the actual footprint of our activities on the extraction of these resources? The EUROSTAT RME[11] method (EUROSTAT 2017) identifies the Domestic Consumption (DC) needed for the production of basic materials, and The Raw Material Consumption (RMC) which is the material footprint taking into account imports and exports of goods and their raw material content. Although calculating the amount of resources embodied into imports/exports differently, our approach leads to similar results for the base year.

The need for raw material is correlated with the incorporation rate of recycled material. The higher the incorporation rate, the less virgin material is required. In order to evaluate the material footprint, we have to consider the incorporation rate inside the analysed region, but also for the products made abroad and imported. In the absence of a detailed statistical description of the very large number of international exchanges, a simplified average abroad incorporation rate has been considered, separating the Euro zone and the rest of the world. It is then necessary to set assumptions about the evolution of these incorporation rates in the future. For instance, the négaWatt scenario assumes that national and abroad rates progressively converge by 2050.

STEP 6: SUSTAINABILITY OF RAW MATERIAL REQUIREMENTS

At the end of the analysis, in order to assess whether a specific need for a raw material remains sustainable or might represent an excessive pressure on the resource, it is necessary to compare the level of needs with available reserves. This raises two important methodological questions:

- How much is available? The Canadian Institute of Mining[12] differentiates between identified, estimated and reserve resources. The reserve is the part of the resource that has undergone preliminary drilling to determine the size of the deposit and the quantity that can be extracted under viable economic conditions. For example, the US Geological Survey, which compiles many statistics, reports a world reserve of 870 kt for copper (USGS 2021), an identified resource of 2,100 kt and an unobserved but estimated resource of 3,100 kt. For lithium, the reserve to date is 21 Mt and the resource is 86 Mt (USGS 2021).
- In the négaMat tool, the available amount is an adjustable assumption that can be changed according to the prospective scenario. For instance, the négaWatt scenario considers that the unchecked opening of new mines may endanger land use, biodiversity, and the lives of indigenous populations, and thus voluntarily limits this parameter to the current reserve (and not to the estimated resource itself).

10. Material Flow Accounts

11. Raw Material Equivalent

12. Canadian Institute of Mining. http://minesqc.com/en/informations-sheets/what-are-mineral-resources-and-mineral-reserves-what-is-the-difference-between-them/

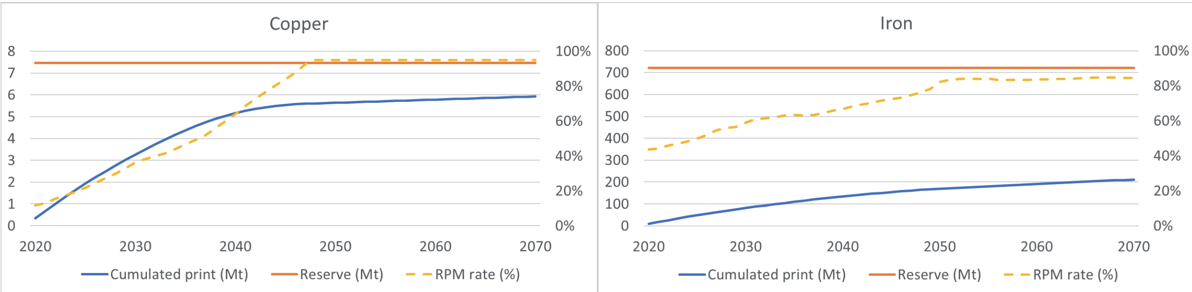

Figure 3. Evolution of the cumulative material footprint and comparison with the fair reserve for iron and copper. The dotted yellow curve also shows the evolution of the incorporation rate of recycled raw material.

- What would be a fair reserve quota for the country (or region) under study? Access to material resources is very unfair today, and it would not be sustainable to assume that the current situation may continue. If we are to respect the SDGs[13] and the 1.5 °C-compatible SSP1[14] scenario defined by the IPCC (IPCC 2021), logic dictates that access to the material quantities available should be more equal, e.g. proportional to the population anywhere on the planet. For example, in a world of 7.87 billion people, France has 67.4 million inhabitants, i.e. 0.86 %. The fair reserve quota for copper is then 0.86 %*870=7.45 Mt, and for lithium 0.86 %*21000=180 kt. Other redistribution approaches would be conceivable, such as taking into account past responsibilities in the use of the resources (but this is not what has been retained in the négaWatt scenario).

Figure 3 shows the comparison of the cumulative evolution of France material footprint with the fair allocation of the resource to the country, under the négaWatt 2021 scenario and for two common materials: iron and copper.

It reveals that iron is not really a critical material. By 2070, the cumulative iron footprint is a quarter of the amount of the fairly allocated reserve. Thanks to highly optimised recycling (85 % incorporation rate), the rate of progression leaves us a margin of 500 years, which is well beyond the predictable. In contrast, copper deserves special attention. To limit its growth, major efforts are necessary and possible. Especially copper may be substituted by alumina in electrical networks and by plastics for plumbing. In addition, recycling incorporation rate is assumed to be 95 % by 2045. Those challenging conditions would give an almost asymptotic trend near 80 % of the reserve. The low rate of progression from 2050 onwards leaves us a margin of about one hundred years before the stocks are exhausted.

Discussion about the material impacts of energy transition

In addition to the results already presented before (that served as illustrations to the négaMat methodological steps), we use the tool to further discuss two common concerns about energy transition: is a 100 % renewable supply materially feasible, and do we risk to run out of lithium if we shift to full electromobility? There are other questions that would undoubtedly be also interesting, but it would exceed what we can provide in the span of this paper.

13. Sustainable Development Goals of the UN

14. Shared Socio Economic Pathway

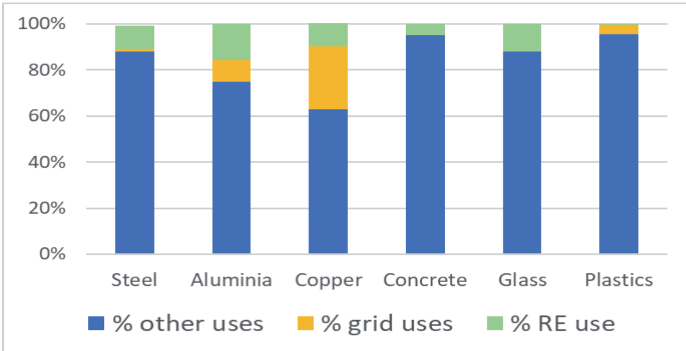

Figure 4. Relative comparison of energy production, networks and other uses for different materials cumulated over the period 2020-2050 under the négaWatt 2022 scenario for renewable development.

IMPACT OF RENEWABLE DEVELOPMENT

As far as renewable energies are concerned, our analysis covers the installation in France between 2020 and 2070 of wind power, photovoltaics, anaerobic digesters, and (bio)gas power plants for possible back-up. The grid power is supposed to increase from 132 GW in 2019 to 295 GW by 2050. Storage facilities, such as electrolysers, methanation plants, as well as stationary batteries are also considered. Electricity grids have also been included. As it is difficult to forecast how electricity grids would evolve even without renewable development, we have considered the total demand for maintenance (cable replacement) and new connections compared to today.

On Figure 4, it can be noted that power generation and grids only require 10 to 15 % of all steel, concrete, glass and plastics. For concrete, it is only 5 %, with the remaining 95 % used for buildings, roads, bridges, etc. For plastics, it is only 4 %. For aluminium (which is not a critical material), the rate is 22 % due to PV panel frames and substitution of copper in cables.

Regarding copper, our results of mass rates (kg/MW) are very similar with the IEA scenario (IEA 2021b) for PV and wind turbines. Although the geographical scope is different,

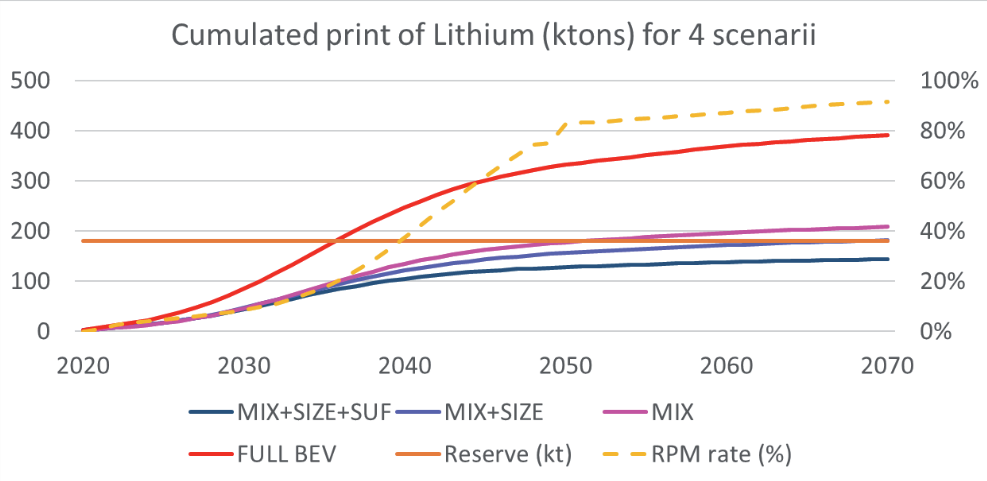

Figure 5. Evolution of the cumulative lithium material print for 4 mobility scenarios: FULL BEV = all electric without sufficiency. MIX = Mix electric and hybrid gaz. MIX+SIZE = MIX + optimization of vehicle size. MIX+SIZE+SUF = MIX+SIZE+sufficiency (reduction of private car use and increased carpooling).

use of copper for renewable energy by 2040 is 6 % of the global amount for the SDS scenario (IEA 2021b) and 10 % for négaMat, which is commensurate for the development of power grids, those shares are respectively 30 % and 26 % (also comparable), but without certainty about what part is exactly due to renewables versus other grid improvements. IEA specifies that no shortage of resources is expected but ore quality is going to decline.

WHAT ABOUT CRITICAL RESOURCES?

The négaMat tool can also be used to study the needs for critical metals, particularly rare earths. However, for France the statistical data is not sufficiently precise and we need to extrapolate from more global data. Conventional silicon technology (mono and polycrystalline) accounts for 5.49 % of the photovoltaic panel market in Europe (JRC 2020). Unlike other technologies (thin films), silicon panels do not contain any rare earth or critical metals. Attention is required on silver, which has seen its share decrease in 10 years from 70 to 15 t/GW in 2020 and will probably reach 3 t/GW by 2040 though technological change (JRC 2020). The cumulative need for panels until 2070 in the négaWatt scenario, taking into account repowering, is 184 GW, which would require about 1,000 t of silver, i.e. a quarter of the reserve quota fairly allocated to France. This proportion would be considerably reduced with an increased recycling of panels.

The content of critical metals in wind turbines (neodymium, dysprosium, praseodymium, terbium and molybdenum) varies substantially from one technology to another (JRC 2020). It is necessary to set a market share forecast for the different technologies, as proposed in a JRC report (JRC 2020). Applying these forecasts in the context of the négaWatt scenario leads to 65.7 GW of expected onshore, and 41.1 GW offshore including repowering between 2020 and 2070. The amount of required neodymium varies between 6.4 % and 10.3 % of a reserve estimated at 99,500 t[15] (BRGM 2015), a rate that does not take into account potential progress in neodymium recycling in the future.

In conclusion, there doesn't seem to be excessive risks of shortages of conventional or critical materials in the massive uptake of renewables. However, improving and increasing recycling would obviously be welcome.

MATERIAL CONSTRAINTS OF ELECTRIC MOBILITY

For transports, we have studied the impact of battery development on cobalt and lithium. The future market shares of the different battery technologies differ from one source to another (T&E 2021; IEA 2021b; Mc Kinsey 2018), but they all foresee further technical progress. We have selected NMC333, NMC811 and LFP[16] with assumptions of improving efficiency.

To examine the influence of different parameters, four simulations have been carried out for all land mobility in metropolitan France, summarised in Figure 5. The common parameter in these simulations is an ambitious assumption of lithium recycling starting as early as 2025.

The results of the modelling show that:

- The FULL BEV simulation supposes a mobility without sufficiency where thermal vehicles are fully replaced one to one by electric vehicles by 2050. In this scenario, France would overshoot its fair reserve of lithium as early as 2035. If all developed countries follow this path, tensions on lithium reserves and between countries would be likely and would start probably sooner than the availability of brand new battery or motorisation technologies. This would lead to an unsafe and risky depletion of the resource, and would not constitute a sustainable mobility model for the world.
- The MIX simulation assumes a moderate shift to electricity with a proportion of BEV[17], PHEV[18] and HEV[19] vehicles,

15. Reserve of 13.5 Mt of oxide or 11.6 Mt of neodymium with an allocation of 0.86 % for France

16. NMC = Nickel Manganese Chromium; LFP = Lithium Iron Phosphorus
17. Battery Electric Vehicle
18. Plug Hybrid Electric Vehicle
19. Hybrid Electric Vehicle

the remainder being fuelled by biogas. When comparing the weight of an NMC811 battery for a BEV sedan (275 kg) with that of a PHEV (67 kg) and HEV (13 kg), it is easy to understand that this mix reduces the pressure on lithium considerably. Nevertheless, the fair reserve quota is still reached by 2050.

- The MIX+SIZE simulation also includes a moderation in the size and weight of vehicles through better matching size to use. With a range of 600 km, a sedan car intended for intercity journeys will have a battery weighing 275 kg on average. For a small city car, the weight is only 47 kg! By differentiating between these vehicle categories, the MIX+SIZE scenario makes further progress. However, the reserve is still reached in 2070.
- The MIX+SIZE+SUF simulation (i.e. the négaWatt scenario) adds key sufficiency trends (less cars, more carsharing) as described in step 1. These trends allow for an asymptotic evolution of the lithium footprint below the reserve, to which a growing level of recycling would enable to reach sustainability by the end of the century.

These striking results are shared by other studies. An extrapolation of the IEA SDS scenario (IEA 2021) leads to a worldwide primary lithium consumption of about 10 Mt in 2040 (half of the proven reserve). Recycling contributes by 6 %. 93 % of the amount is used for electric cars. These results appear consistent with our négaMat simulations: in 2040, 55 % of the global reserve is already consumed. After 2040, the IEA report warns on increasing demand and potential bottlenecks on raw material supply.

Limits

With about 800 parameters, each covered by yearly assumptions over 50 years, négaMat is a powerful 'cradle-to-grave' material simulation tool. It contributes to better analysing the impacts and material footprint of energy transition scenarios, as well as the industrial consequences of an approach based on sufficiency, efficiency, circular economy, and renewables.

Given the complexity of the task of finely modelling all aspects related to materials and consumption of goods, this tool has methodological limits. Among the main ones:

- The material / CEG relationship matrices were built by cross-checking the distribution of uses of a material (top down approach) and the average composition of a product (bottom up approach). The resulting compromise leads to uncertainties, that should ideally be quantified in order to assess the overall robustness of the modelling.
- Even if forecasts of material substitution are feasible for major sectors such as construction, transports, energy and packaging, it would be useful to extend the scope to further product groups.
- Some sectors such as digital technologies include very different products, and their material consumption is only averaged. The evolution of the average in the assumptions does not take fully into account potential material substitutions and the replacement of certain products by others. In any case, forecasting the future of digital devices is a very tricky task considering the speed of technological development in this sector.
- The level of modelling is not always sufficient to account for precious or rare materials. To analyse metals such as indium, gold or rare earths, it would be necessary to develop additional modules (for which the statistical data is sometimes obsolete or even non-existent).
- The tool has been designed to work with various types of scenarios and assumptions. Implementing it in other EU Member States has been considered in the preparation of a major European energy transition scenario currently led by the négaWatt Association with many partners (Marignac et al 2021). However, it is constrained by hurdles relating to data access and cross-checking issues. Better understanding these methodological difficulties would improve the replicability of the négaMat approach.
- Further comparisons of our findings with other studies and scenarios would be insightful and could reinforce the robustness of our tool. However, such comparisons are often methodologically complex, as available studies vary in geographical perimeters, scopes of the material flow and footprint analysis, energy transition assumptions, and approaches to material reserves. It would require a thorough analysis and access to the detailed modelling data and hypotheses of each study. This could be the topic of a future research activity and paper.

Conclusion

négaMat is an ambitious tool, still under development, that has not yet achieved all of its accomplishments. One of its important added-values so far is that it allows a clearer distinction between the contributions of sufficiency, efficiency, circular economy, international trade, and industrial relocation when assessing the energy and material impacts of prospective scenarios. It has been a valuable complement to energy transition scenarios such as the négaWatt scenario for France.

It also helps identifying the sectors and trends that have the highest potential impact on material consumption, as well as the industrial activities that require special attention in the energy transition. For example, négaMat can assess the impact of moderating the need for the construction of new buildings and encouraging renovations, as well as promoting sufficiency, modal shift, and electrification in mobility.

Among our key findings is the comparison of these material needs with available reserves. When applied to France and the négaWatt scenario, and taking into account a fair distribution of global reserves per capita, we found that there should be no excessive risks of material scarcity for conventional materials, with the exception of copper. For the latter, substitution of aluminium in power grids and high levels of recycling will be key. Regarding critical materials, a 100 % renewable scenario should not lead to excessive risks of resource depletion. However, the situation is much more strained for lithium and cobalt if there is a full-scale shift to electric vehicles. This would only be sustainable if significant sufficiency measures are taken in the mobility sector, vehicle size is limited, and electrification is complemented by other propulsion systems (e.g., based on biogas).

Further activities and developments are planned for the future, such as using the tool to compare the impacts of other transition scenarios in France (RTE[20] and updated SNBC[21]) or at the European level (provided sufficient data is available). A collaboration with economists from the Rousseau Institute[22] is also underway to assess the financial investments needed to achieve the material and industrial shifts that have been assessed through négaMat.

References

ADEME, 2020. Transition industrielle – Prospective énergie matière: Vers un outil de modélisation des niveaux de production.

ADEME, 2021. Prospective Transition 2050.

Antoine Beylot, Dominique Guyonnet, Stéphanie Muller, Stéphane Vaxelaire, Jacques Villeneuve, 2019. Mineral raw material requirements and associated climate-change impacts of the French energy transition by 2050. *Journal of Cleaner Production, Volume 208*.

BRGM, 2015. Fiche de synthèse sur la criticité des métaux - Le néodyme.

EUROSTAT, 2017. Documentation of the EU RME Model.

EUROSTAT, 2018. Economy-wide Material Flow Accounts Handbook.

HCP, 2021. Reconquète de l'appareil productif : la bataille du commerce extérieur.

IEA, 2021a. World Energy Model Documentation.

IEA, 2021b. The role of critical minerals in energy transitions.

IPCC, 2021. Climate Change - The physical Science Basis.

JRC, 2018. Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data.

JRC, 2020. Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system.

Yves Marignac, Stéphane Bourgeois, Mathilde Djelali, Nicolas Taillard, Janis Brizga, Marta Garcia, Radu Dudau, Luisa Cordroch, Dimitri Lalas, Yves Marenne, Gunnar Boye Olesen, Philippe Bovet, Yannis Sarafidis, Silvia Erba, Lorenzo Pagliano, Léo Coppens, Benjamin Best, Johannes Thema, Francisco Ferreira, 2021. Scaling-up energy sufficiency on a European level through a bottom-up modelling approach: lessons and perspectives. *Proceedings of the eceee Summer Study conference*.

Mc Kinsey, 2018. Lithium and cobalt: A tale of two commodities.

négaWatt Association, 2018. Energy Sufficiency.

négaWatt Association, 2021. Scénario négaWatt 2022.

SOLAGRO, 2016. The Afterres 2050 scenario.

Stefan Pauliuk, Niko Heeren, Peter Berrill, Tomer Fishman, Andrea Nistad, Qingshi Tu, Paul Wolfram & Edgar G. Hertwich, 2021. Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nature communications*.

T&E - Transport and Environment, 2021, From dirty oil to clean batteries.

USGS, 2021. Mineral Commodity Summaries.

Takuma Watari, Benjamin C. McLellan, Damien Giurco, Elsa Dominish, Eiji Yamasue, Keisuke Nansai, 2019. Total material requirement for the global energy transition to 2050: A focus on transport and electricity. *Resources, Conservation and Recycling, Volume 148.*

Acknowledgements

The authors warmly thank all the expert contributors to this paper and to the négaMat tool, in particular Adrien Toledano, Adrien Jacob, Thierry Hanau and Stéphane Chatelin.

20. Réseau de Transport Electrique: see https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques

21. Stratégie Nationale Bas Carbone: see https://www.ecologie.gouv.fr/strategie-nationale-bas-carbone-snbc

22. https://institut-rousseau.fr/s