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Highlights

Dynamic modeling of global fossil fuel infrastructure and materials needs: overcoming a lack of available data

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- Fossil fuel infrastructures are modeled from 1950 to 2050.
- A dynamic material flow analysis (MFA) is developed and applied.
- Embedded materials, energy and CO₂ emissions are estimated.
- A potential to build renewable technologies from fossil fuel infrastructures is identified.
- To be ambitious, decommissioning strategies should enhance in-use steel recycling.

Dynamic modeling of global fossil fuel infrastructure and materials needs: overcoming a lack of available data

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Abstract

The low-carbon energy transition requires a widespread change in global energy infrastructures which in turn calls for important inputs of energy and materials. While the transport and electricity sectors have been thoroughly analyzed in this regard, that of the hydrocarbon industry has not received the same attention, maybe in part due to the difficulty of access to the necessary data. To fill this gap, we assemble public-domain data from a wide variety of sources to present a stock-flow dynamic model of the fossil fuels supply chain. It is conducted from 1950 to 2050 and along scenarios from the International Energy Agency. We estimate the concrete, steel, aluminum and copper requirements for each segment, as well as the embedded energy and CO₂ emissions through a dynamic material flow analysis (MFA) model. We find that (i) the material intensities of oil, gas and coal supply chains have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption; and (iii) recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll. Furthermore, we highlight that regional decommissioning strategies significantly affect the potential of material recycling and reuse. In this context, ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures.

1. Introduction

Human society and nature interactions have experienced a radical change over the 20th century, driven by the rapid industrialization of Western economies and that of several emerging countries in more recent years [1, 2, 3]. Economic expansion is largely attributable to the availability and affordability of fossil resources, whose high energy return on investment (EROI) have triggered productivity gains [4, 5]. The abusive use of energy has however unleashed unprecedented climate and ecological damages, jeopardizing the planet's life supporting functions [6].

As a tentative response, 196 countries gathered during the 2015 United Nations Climate Change Conference of Paris and agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels. Such a target requires deep transformations of our society including, but not limited to, a shift away from fossil fuels to low-carbon energies, which calls for important quantities of energy and materials [7, 8, 9, 10, 11, 12]. While the transport and electricity sectors have been thoroughly analyzed, the hydrocarbons have not received the same attention, to the best of the authors' knowledge¹. This may in part be due to the fact that infrastructure data for the fossil fuel industries are relatively difficult to access, and are often commercially

sensitive. This makes the analysis of this sector particularly complicated for the scientific community not affiliated with fossil fuel producers or operators. To fill this gap, we present a stock-flow dynamic modeling of the infrastructures as a part of the fossil fuels supply chain, from 1950 to 2050 and along scenarios from the International Energy Agency (IEA). We estimate the concrete, steel, aluminum and copper requirements for each segment, as well as the embedded energy and CO₂ emissions through a dynamic material flow analysis (MFA). Finally, the potential of recycling steel from decommissioned fossil fuel infrastructures to build power technologies is further discussed.

This paper is structured as follows. Section 2 examines the existing literature. Section 3 describes the methodology and data used. Section 4 presents the results, section 5 discusses them, section 6 details the robustness and limitations of the study and section 7 concludes.

2. Literature review

2.1. An evolving field

Modeling the stocks and flows of metals or minerals that make the infrastructures has been a research topic for more than twenty years. Early publications focus on static global or regional MFA of the base materials used over the 20th century—such as copper and steel. The Stocks and Flows Project (STAF) launched in 2000 by the Center for Industrial Ecology is one example [13, 14, 15, 16]. These studies allow for top-down analysis, relying on material databases

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¹The relevant literature is reviewed in Section 2.

such as the International Copper Study Group [17] and the World Bureau of Metal Statistics [18]². The authors aim at providing insights in the material cycles within human society, and quantifying the losses-dissipation, landfills-and the potential of secondary use. Materials analysis has progressively evolved towards dynamic studies, and bottom-up approaches³ enable a better understanding of the technological drivers of raw materials demand over time. A significant number of these publications deal with the building sector because of waste generation and secondary resources aspects [19, 20, 21], stock drivers [22], the effect of lifetime [23] or materials demand in transition scenarios [24, 25]. More recently, several authors also analyze the material facet of the energy sector with growing consideration on the consequences of the ongoing energy transition.

2.2. The energy transition challenge

The transition requires vast amounts of minerals and metals [9, 26, 27] due to a significantly higher material intensities of renewables [28, 29, 8] and new technologies [30]. Vidal et al. [8] state that "a shift to renewable energy will replace one non-renewable resource (fossil fuels) with another (metals and minerals)", while Li et al. [31] point out the trend toward a "more metal-intensive energy future" as renewable energy are increasingly being developed. Recent dynamic MFA or simple flow analysis⁴ focus on quantifying the prospective demand in non-energetic materials for a low-carbon energy system in various institutional scenarios (e.g. IEA-450, IEA BlueMap, NDRC scenarios), non-governmental scenarios (e.g. Greenpeace, WWF-Ecofys) or academic scenarios (e.g. SSP). Researchers show that the most environmentally ambitious scenarios display the highest material constraints [34, 35], and identify two areas of concern: criticality, which is defined as the levels of importance in use and availability of a material [36], as well as environmental and energy impacts.

Among low-carbon technologies, the most significant material constraint could stem from solar PV and wind turbines along with power storage [37, 35] and the transmission and distribution networks [38]. A higher level of pressure for rare-earth elements (REE) than for base metals is emphasized, with potential constraint in REE for each PV solar technology [29, 39, 40], region-specific supply risk [41, 42, 43, 44, 45] which require future increase in numerous metal supplies [46, 47] with potential limitations in reserves which could hamper future projects [48]. The downscaling

²A top-down study is defined as a modeling relying on input output tables which assesses stocks from a flow analysis.

³Bottom-up modeling focuses on describing parts of the system in details and then conducting a part-whole modeling.

⁴Further modeling on the topic has been conducted through Life-Cycle Analyses. For example, Kleijn et al. [28] examine the metals demand and CO₂ emissions of low-carbon energies for the power sector, in regard to four different scenarios, while Koning et al. [32] estimate the required extraction of 11 metals until 2050 under technology-specific low-carbon scenarios, for the electricity and road transportation systems and Hertwich et al. [33] take on the issue by approaching the needs in steel, cement, copper and aluminum for power generation technologies in the IEA BLUE Map and Baseline scenarios.

of a global issue to a political scale also paves the way to the criticality literature, estimating potential supply risks for various situations [49, 50, 51, 52, 53, 54, 55]. Future constraint on raw materials also comes from the energy and environmental impact of their production. While the criticality research field focuses on technological materials, impact analyses are mainly conducted on base materials though the link between energy and materials.

2.3. Recycling and the energy-raw materials nexus

The energy-material nexus remains insufficiently addressed in energy transition scenarios, and several authors call for a better understanding of its impact [34, 35] and for a better understanding of the assessment of the emission costs and gains of the energy transition [31]. Elshkaki [39] further estimates that the global energy demand of material production for photovoltaic solar technologies could represent up to 12% of solar power generation in the IEA-450 scenario by 2050, and its CO₂ emissions could reach up to 2.2% of the global emissions. Several policy tools are incorporated in the publications, in order to discuss the upcoming challenges. First, recycling could diversify supply sources to reduce pressure on primary materials [35, 56] for geopolitical purposes [46], and environmental concerns as dilution of metals in deposits rises [57, 58]. However, the short-term objective of energy transition is equivalent to lifetimes of technologies, thus limiting the potential of recycling before 2050 [9, 59, 45]. Second, studies emphasize that material supply pressure could be mitigated by reducing the material content in power generation technologies [40, 34].

2.4. Toward more systematic analysis

The upcoming material challenge is also addressed in integrated assessment models (IAMs), as a necessary step to produce "biophysically more consistent descriptions of society's future metabolism" [60]. IAMs allow to quantify the material requirements in scenarios of low-carbon transitions from a system perspective. For instance, Hache et al. [61, 62] and Seck et al. [63] use a modified version of the TIMES model (TIAM-IPFEN) to study the critical materials for the transportation sector electrification, the impact of the future power generation on cement demand and the copper availability up to 2050. Sverdrup et al. [64, 65] and Olafsdottir and Sverdrup [66] focus on nickel, helium, copper, zinc and lead using the WORLD7 model. Using on the MEDEAS integrated assessment model, Capellán-Pérez et al. [67] assess the material investments necessary for a transition to renewable energies, in a Green Growth narrative, concluding it to be unrealistic.

The literature on the metals and minerals supply pressure stemming from the energy transition has been recently booming. However, despite the large share of fossil fuels in the global primary energy consumption, researchers have to date and to the best of the authors' knowledge not explored in detail the material requirements of the industry on a global

scale and in a long-term perspective⁵. This study attempts to tackle this question and fill the relative literature gap that exists today. To do so, the following methodology is carried out.

3. Methods and data

3.1. The *DyMEMDS* model

The *DyMEMDS* (Dynamic Modelling of Energy and Matter Demand and Supply) model is developed to estimate the needs in primary and recycled materials, as well as the energy and CO₂ emissions resulting from the extraction of these materials, along global or national energy scenarios. The entire energy chain is covered from primary energy to final consumption with forty technologies of energy production, storage, transport, transformation along three sectors of energy use: transport, construction and industry [58]. A multi-sector analysis of material stocks and flows is prepared for further work. Only the fossil fuels supply chain module is described in this section⁶.

Historical infrastructures data and energy scenarios are used to model the hydrocarbon supply chain. When no data are found, we use Gompertz functions of Gross Domestic Product (GDP) and population or correlations with the energy supply. Technological material intensities, recycling rates, normal lifetime distributions and end-of-life recycling rate (EOL-RR) are used to estimate retrospective and prospective flows and stocks of materials. Indirect impacts of the materials demand are evaluated relying on state-of-the-art works on embodied energy and CO₂ emissions of materials. A local sensitivity analysis is finally conducted to assess the effects of the mean lifetime and materials intensities uncertainties. Figure 1 presents the methodology lying behind the *DyMEMDS* model.

The most important box, 'raw materials stocks and flows', can be extended for further clarification. The *primary production flow* in tons/year feeds an *in-use stock* in tons of materials immobilized in the infrastructure. At the end of the lifetime of the infrastructure considered, the *in-use stock* is reduced by the flow of materials to be recycled. Normal lifetime distributions are considered in this study. The *losses flow during the recycling process* thus feeds the *cumulative losses stock*, while the *end-of-life recycling flow* builds a *recycled stock*. The latter then allows for secondary production of a *recycled materials flow*, which is ultimately reused in the *in-use stock*. New infrastructures thus mobilize primary and secondary production. In the specific case of a reduction of the infrastructure stock, there is a dismantling before the end of the life span. An *unused flow* is then created, ultimately feeding an *unused stock*, which then follows a recycling path. This stock could eventually produce a *reused flow* for other infrastructures. The infrastructures embodied energy and CO₂ emissions are finally estimated through assumptions about the material production energies

⁵Only Wang et al. [68] proposed an estimation of the steel weight of the drilled wells and the transportation pipelines in China.

⁶A detailed description of the inputs is provided in the Supplementary Information.

and CO₂ emissions. Figure 2 details the key loop used in the *DyMEMDS* model to estimate the stocks and flows of materials during the construction and maintenance of the infrastructure.

3.1.1. Infrastructures

The infrastructures considered in this study are separated into three main segments according to the historical distinction made in the petroleum industry: upstream, midstream and downstream activities. It totals 11 technologies used in supply activities from exploration to distribution. The fossil fuels supply chain encompasses a larger number of infrastructures some are excluded due to a lack of data (oil tanks, national coal transport and processing), large disparities in the data obtained (drilling rigs)⁷, or difficulties to model future distribution in technologies related to decentralized demand (petrol stations and compressed natural gas services). Figure 3 displays the infrastructures typology used in *DyMEMDS*.

3.1.2. Dynamic evolution of infrastructures

A stock-driven approach is conducted in order to model the dynamic evolution of fossil fuels associated infrastructures. The evolution of technology stocks is assumed to be correlated with the fossil fuels production (eq 1)⁸. Infrastructures are then attributed to a fossil fuel, either fully (eg. oil tankers only carry petroleum products) or in a proportionate manner (eg. wells produce both oil and gas). In this case, the evolution of each infrastructure stock is correlated to its related share of fossil products in the supply chain using historical and prospective shares of oil, gas and coal traded from BP [71] and the IEA⁹ [72].

Substantial annual variations are observed in hydrocarbon production, but only wells experience significant upwards and downwards annual changes. An adapted function of each fossil fuel supply was established to prevent these variations. It is defined as a third-order exponential moving average¹⁰ (eq 2), which enables both to smooth out the short-term impact of price variations on production and to overweight the more recent values.

$$S_{t,i} = \alpha_i \cdot \text{EMA}_{3,P_i}(t) \quad (1)$$

$$\text{EMA}_{3,P_i}(t) = P_i(t) \cdot 0.5 + \text{EMA}_{3,P_i}(t-1) \cdot 0.5 \quad (2)$$

⁷Significant disparities were observed in both material intensities and rigs census. It is explained by both the recent and rapid development of floating structures and the wide range of structure sizes.

⁸Some researchers rely on logistic or Gompertz functions, see for instance the work of Gutiérrez et al. [69] for vehicle stocks and Huang et al. [70] for buildings stocks. The link between hydrocarbon technologies and energy prices, as well as political decisions (e.g. OPEC's influence on prices) hamper the application of this methodology here.

⁹A high share of traded oil is noticed, while coal and natural gas are mostly consumed locally.

¹⁰A moving average is defined as an average of a predefined number of past values in a dataset, which are weighted equally in its simple form. In its exponential form, the weight of the values decreases exponentially, which enables to overweight the more recent data.

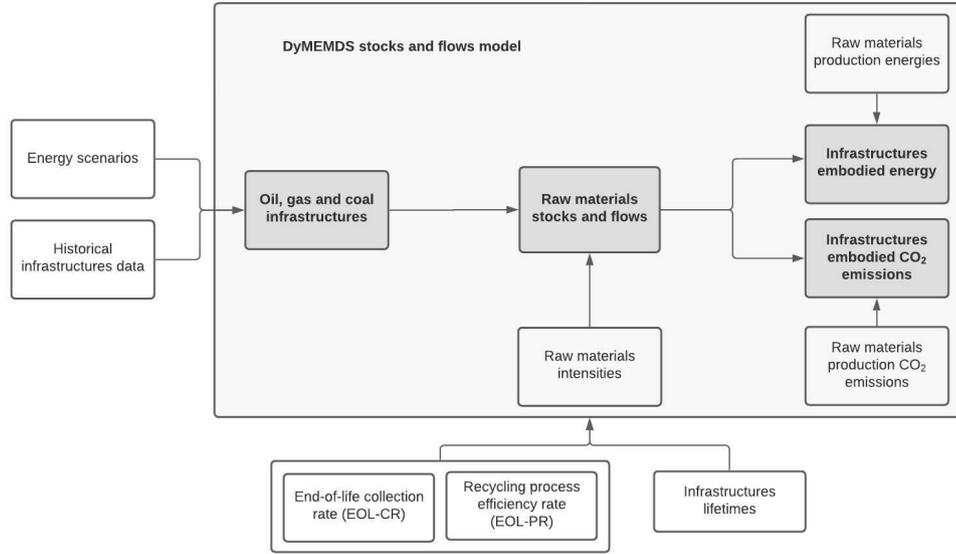


Figure 1: Simplified methodology lying behind the *DyMEMDS* model.

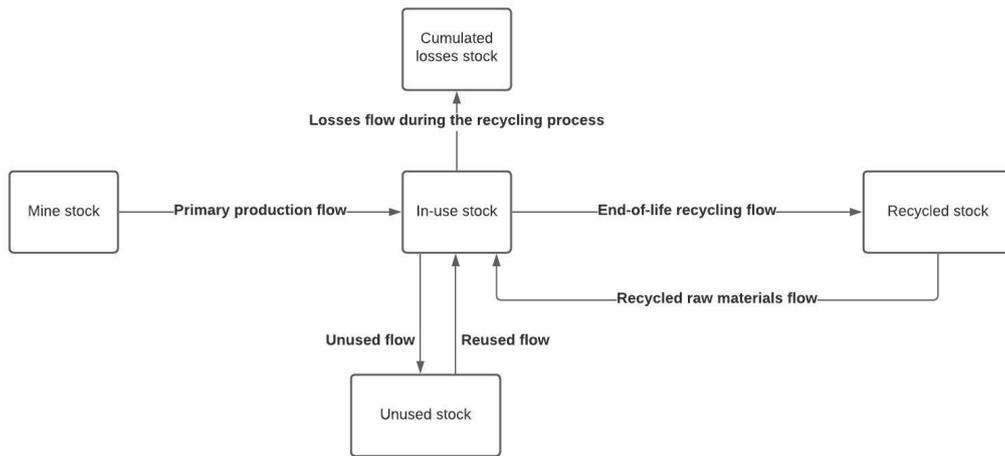


Figure 2: Key loop used in the *DyMEMDS* model to estimate the stocks and flows of materials during the construction and maintenance of the infrastructure.

With $S_{i,t}$ the stock of infrastructure i in the year t , α_i the correlation coefficient for the infrastructure i and $EMA_{3,P_i}(t)$ the third-order exponential moving average in year t of the hydrocarbon supply P_i related to the infrastructure i .

3.1.3. Material recycling

This study focuses on four bulk materials, namely aluminum, concrete, copper and steel, which represent a significant share of material consumption [73], energy demand and environmental impacts of material production [74]. No material substitution is assumed for the base materials, but some studies present contrasted views, e.g. Sverdrup et al. [75, 76] A dynamic end-of-life recycling rate (EOL-RR) is assumed for each material, encompassing both the recycling process efficiency rate (EOL-PR) and the old scrap collection rate

(EOL-CR), as defined by Glöser et al. [77] and Graedel et al. [78]. A global and multi-sectoral averaged EOL-CR is assumed in this study. Table 1 summarizes the considered rates.

	1950	2010	2030	2050
Concrete	0	0	0	0
Steel	0.6	0.7	0.74	0.84
Aluminum	0.39	0.45	0.48	0.54
Copper	0.34	0.4	0.42	0.48

Table 1
End-of-life recycling rates of the considered materials.

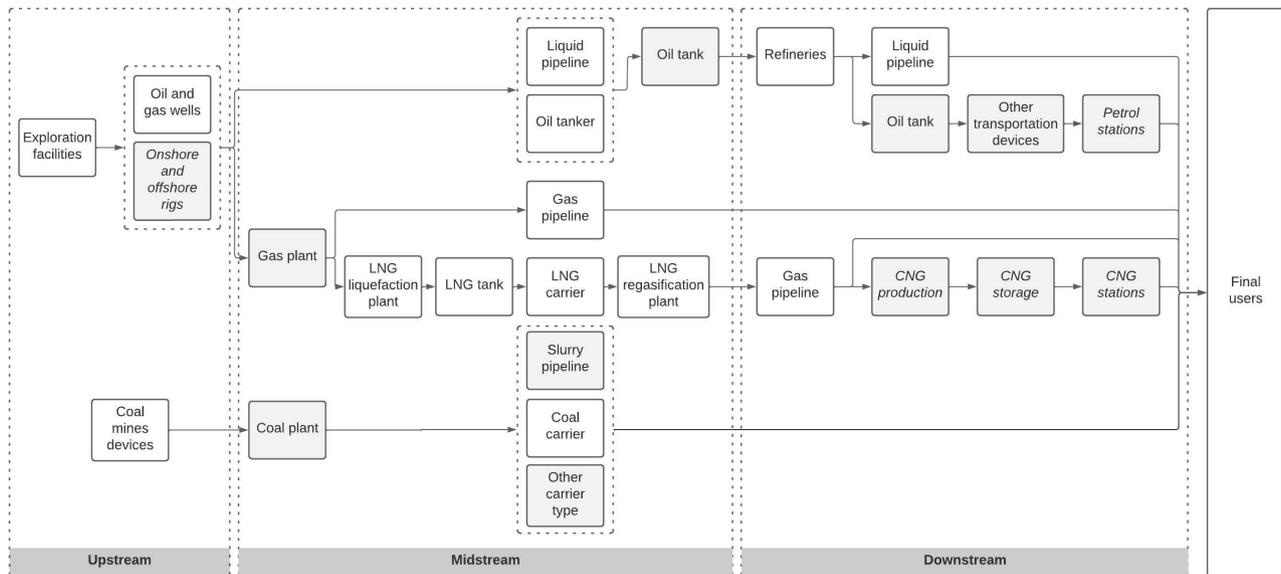


Figure 3: Oil, gas and coal infrastructures from production to final users supply. The infrastructures in grey and italic are not considered in this study.

3.2. Materials, energy and CO₂ intensities

The material requirements for the hydrocarbon production infrastructures are obtained from Monfort et al. [79]. The dataset extensively relies on the Ecoinvent database¹¹, which provides with useful data for a large panel of infrastructures. Remaining intensities are obtained from both academic publications and private firms reports. The material intensity data used in this study come mostly from sources dating from the 1960s to the 2000s. The correlation between infrastructure stock and hydrocarbon production justifies the temporal validity of these data for the study, since nearly 60% of historical oil production and 57% of historical gas production took place between 1960 and 2000 [80]. The embodied energies of primary and secondary materials are dynamic between 1900 and 2100, and their scope extends from cradle to gate. Primary metals embodied energies depend on both the ore grade of the mined material and the technological improvement of production technologies [81, 82, 83]. Data from Vidal [84] and Vidal et al. [85] are considered for copper, aluminum, and steel (assuming all steel alloys represent steel). The production energy of concrete is estimated from a multi-regional approach to cement production and clinker energy intensities. Energy of metal recycling is assumed to be consumed during secondary production as a fraction of the energy of primary production. An annual technological progress in production processes of 1% is estimated between 1900 and 2100, as well as a floor value equal that of the thermodynamic limit of the recycling processes. The minimum energy of recycling equals the melting energy of each metal plus the energy of collection and sorting. CO₂ intensities of materials production are also considered in the model:

¹¹The Ecoinvent database contains life-cycle inventory data for a wide range of technologies, with a thorough documentation on their hypothesis and validity (e.g. geographical and temporal).

they are dynamic and vary according to the CO₂ intensity of the energy consumed over time. We consider a decreasing intensity since 1900, and assume that 83g of CO₂ are emitted by MJ of consumed energy in 2015. This value is supposed constant from 2015 onward.

3.3. Scenarios

Two scenarios from the International Energy Agency (IEA) are selected: the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 (NZE) [86, 87].

- The STEPS considers government measures already in place or officially announced and envisions a quick return to pre-COVID-19 consumption levels. By 2050, the electricity mix is 55% renewable, coal consumption falls by 15% from 2020, oil consumption rises by 15% and gas consumption rises sharply by 50%. The effects of climate change are limited to an average global warming of 2.7°C in 2100 compared to pre-industrial levels (Fig. 4).
- The NZE scenario offers a more ambitious approach. Considered by the IEA as a deepening of the former Sustainable Development Scenario (SDS) [88], it assumes the achievement of a carbon neutrality of the energy sector by 2050, which allows to limit the average global warming to 1.5°C. Renewable energies play a predominant role, with solar and wind power accounting for nearly 70% of electricity production in 2050. Moreover, energy demand falls by 7% between 2020 and 2050, with a decline in coal consumption of 90%, 75% for oil and 55% for gas over the same period (Fig. 4). When some information is missing, data from the Sustainable Policies (SP) scenarios are used instead [72].

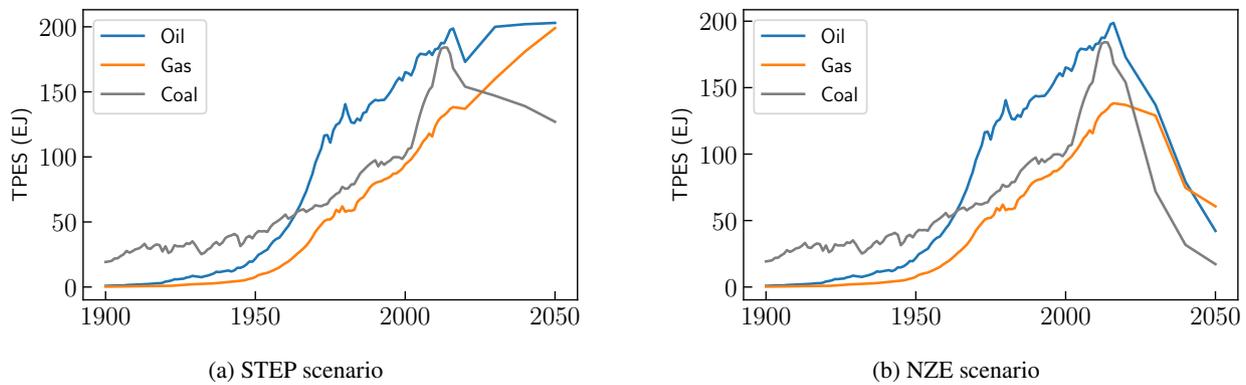


Figure 4: Historical and prospective global primary energy supply from fossil fuels in the STEPS and NZE scenarios.

3.4. Sensitivity analysis

A local sensitivity analysis was conducted to assess the impact of the input parameters uncertainties on outputs. Previous studies showed the significant share of lifetime uncertainty impacts in sensitivity analysis [23, 89], and further pointed out that the standard deviation and shape of lifetime distributions had little effects on the results compared to the mean value [90, 77, 91]. The sensitivity analysis therefore focuses on the mean lifetime value in the normal distribution, for which variations of $\pm 20\%$ were computed.

4. Results

4.1. Infrastructures

4.1.1. Gas

The gas infrastructures experience a significant increase in the STEPS and a drop after a peak in 2030 in the NZE scenario. The largest increase in infrastructure occurs for gas in the STEPS. The world fleet of LNG carriers reaches more than 1200 units in 2050 in the STEPS, the storage capacity exceeds 136 million cubic meters and the total capacity of liquefaction and regasification plants doubles to more than 3700 billion cubic meters between 2020 and 2050. Conversely, the carbon neutral NZE scenario involves 40% decrease in total LNG supply chain capacity between 2020 and 2050. The number of LNG carriers drops to 376, after peaking at 788 vessels in 2030. The global pipeline network displays a similar trend, raising to 15 million kilometers in 2050 in the STEPS, and dropping to less than 5 million kilometers in the NZE scenario (Fig. 5). The modeled values of the infrastructures stocks are available in the Supplementary Information.

4.1.2. Oil

Two trends of the infrastructure of the oil supply chain can be identified. After a slight increase between 2020 and 2030, the stock stabilizes in 2030 in the STEPS, while a slowdown is observed in the NZE scenario between 2020 and 2025 and followed by a substantial reduction. This unveils a significant constraint on the infrastructures mobilized in the oil supply stages. Pipelines, tankers and refineries experience a drop in their stock by nearly 75% between 2020

and 2050. The number of pipelines decreases to 242,000 km, and the tanker fleet to only 150 Million Dead Weight Tons (MDWT)¹². In the STEPS, the growth of the traded oil shares combined with the rise of the oil consumption induces a faster development of transport infrastructures than storage or refineries. The stock of petroleum products pipelines reaches 1.08 million kilometers in 2050, and the fleet of tankers 670 MDWT, while the global refining capacity increases to nearly 108 million barrels per day. Wells development depends the cumulative consumption. The number of wells thus slightly raises from 1.35 million to 1.4 million in 2050 in the STEPS and experiences a substantial decrease to 300,000 in the NZE scenario (Fig. 5).

4.1.3. Coal

The two global scenarios consider a drop in coal consumption between 2020 and 2050, albeit of varying magnitude. The bulk carrier fleet thus collapses over the period and finally reaches 150 MDWT and 21 MDWT in 2050, respectively, in the STEPS and NZE scenarios (Fig. 5).

4.2. Materials

Steel is the main source of materials requirements for fossil fuels. It represented nearly 70% of the sector materials demand between 1950 and 2020, and the remaining 30% is mainly concrete. In contrast, aluminum and copper consumption represent 0.04% and 0.06%, respectively. However, these proportions conceal major disparities in absolute annual consumption, depending on the evolution of the oil, gas and coal markets. A first peak in consumption can be observed in 1973, following the increase in hydrocarbon consumption since the early 1940s. The annual demand for concrete raised from 2.8 Mt/yr to 42 Mt/yr and steel consumption grown from 4.4 Mt/yr to 64 Mt/yr between 1940 and 1973. The succession of two oil peaks in 1973 and 1979 then reduced the demand for materials to almost zero for steel, concrete and copper, while the dependency of aluminum demand to oil products infrastructures drove its value to zero. The knowledge of historical material demand

¹²The DWT is a unit of the total carriage capacity of a vessel, including all types of goods and passengers.

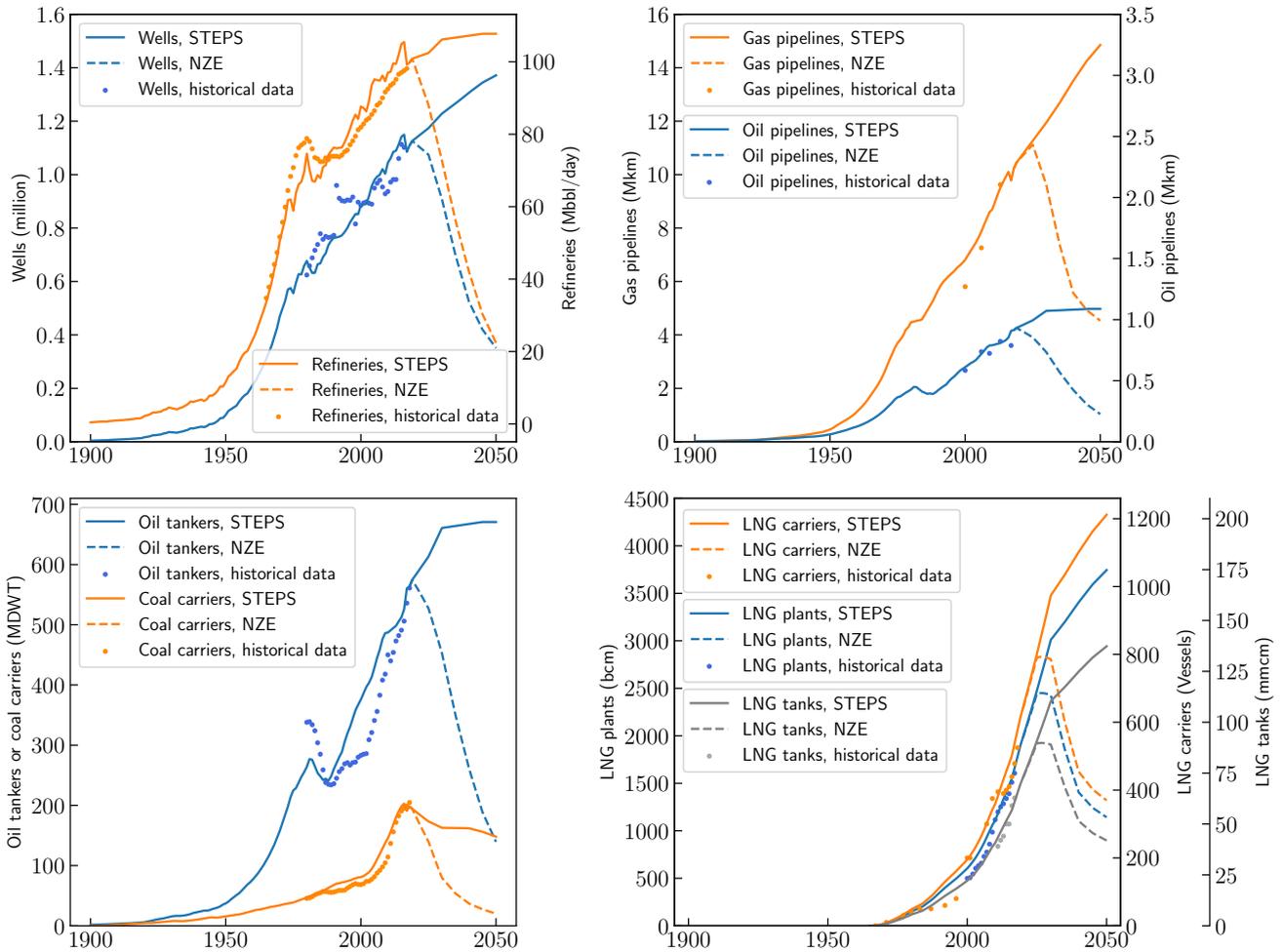


Figure 5: Historical and prospective stocks of key infrastructures in the STEPS and NZE scenarios, global scale.

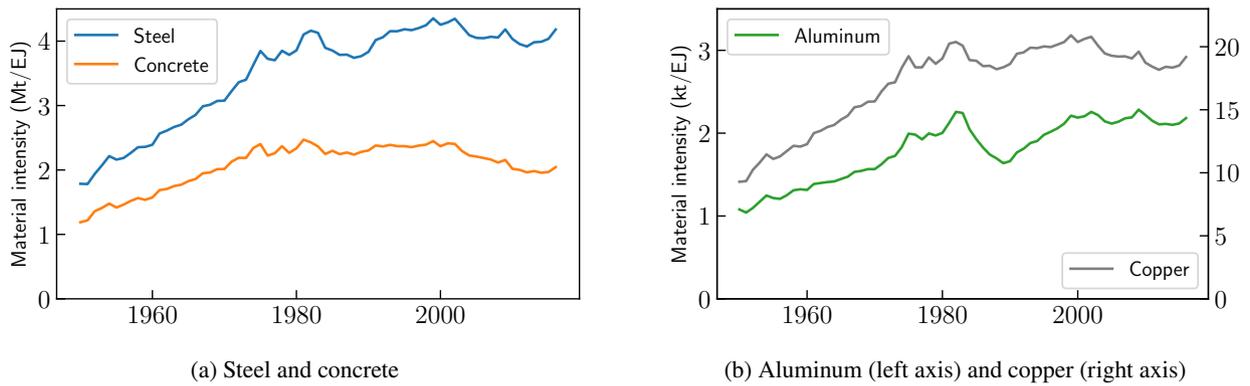


Figure 6: Historical material intensities in the fossils supply sector from 1950 to 2016.

allows to estimate historical materials intensities for the global fossils supply chain. Their values between 1950 and 2016 are displayed in Fig. 6. We observe a stabilization of their level since the 1970s, despite a significant drop in the sector’s aluminum intensities in the 1990s.

4.2.1. Material consumption in the scenarios

The historical distribution pattern of the cumulative consumption among the four structural materials remains similar in the scenarios. Steel accounts for 70% of the cumulative sectoral material demand between 2020 and 2050 for the STEPS and over 77% in the NZE scenario. The share of concrete in the total consumption experiences a decrease in

the scenarios considered and aluminum and copper shares remain low. The increase of the hydrocarbons demand until 2025 induces higher peak material requirements than those observed historically. The steel, aluminum and copper demands respectively reach 96 Mt, 80 kt and 0.44 Mt in 2025. In the STEPS, the cumulative flow of steel needed between 2020 and 2050 is 2.4 Gt and that of concrete exceeds 1 Gt. This represents 1.4 years of total global production at 2020 levels for steel, and a small amount compared to an estimated total global production of 20 to 24 Gt in 2020 for concrete [92, 93]. The NZE scenario requirements reach 0.34 Gt for steel and 0.1 Gt for concrete. An identical trend is observed for copper and aluminum. The cumulative demand for copper reaches 11 Mt in the STEPS, compared to a total global production of 20 Mt in 2020, and cumulative demand drops to only 1.5 Mt in the NZE scenario. The total aluminum requirements amount to 0.86 Mt for the STEPS and 51 kt for the NZE, which respectively represents 1.3% and 0.08% of 2020 total global production. The combination of this lower consumption and the identical historical stock allows the NZE scenario to rely more heavily on recycled materials. The proportion of recycled metals reaches more than 80% in the NZE scenario, and 29% to 42% in the STEPS scenario. The stock of concrete reaches more than 1.2 billion tons in 2050, while a substantial drop to 0.35 billion tons is observed in NZE scenario. This trend is similar for the three structural metals, and steel stock amounts to 2.9 billion tons in the STEPS and 0.82 billion tons in the NZE scenario in 2050 (Fig. 7). The peaks and drops observed in the stock evolution in 2017 are explained by the differences between the historical and prospective data.

4.2.2. *Material consumption per fossil fuels and segments*

The oil and gas infrastructures represent most of the raw materials, which is explained by the complexity and decentralization of the supply infrastructures. The aluminum is entirely consumed by the oil product pipelines for all scenarios—due to underlying data—and the midstream segment therefore dominates aluminum consumption. Conversely, the split between oil and gas remains more equal for concrete, steel and copper, although there is a clear trend towards an increase in the share of gas in materials demand over time. The share of gas in concrete consumption evolves from 30% to nearly 60% between 1950 and 2050 and from 45% to nearly 70% over the same period for steel. The distribution between the segments also shows important differences. The upstream segment represents most of the concrete demand between 1950 and 2050—in the production of wells—while a more equal distribution is observed for steel and copper.

4.2.3. *Material consumption per infrastructures*

The bulk materials demands show high level of domination of some infrastructures. Wells represented about 80% of concrete consumption until 1970 and their share declined with the progressive development of gas pipelines,

which share reaches about 25% in 2050 in the STEPS. A slight increase of the oil pipeline share was noticed, finally reaching 5% in 2050. The gas network also carries most of the sectoral steel demand. Its share experienced a rise from 45% of the consumption between 1950 and 1970 to almost 60% in 2050 in the STEPS. The wells have an opposite profile and the oil pipelines represent 20% of steel demand over the period. Copper is mostly consumed in steel alloys in the hydrocarbon supply chains. It therefore displays a distribution profile similar to steel. Finally, nearly all aluminum is consumed in oil pipelines—due to the underlying data.

4.2.4. *Opportunity and uncertainties in the future amount of recycled materials*

The share of recycled materials in the hydrocarbon supply chain increased over time. It evolved from 3% in 1950 to nearly 20% in 2020, with disparities depending on the metals considered. A future stabilization or drop in the fossil fuels demand could further induce a substantial rise of the recycled share of metals inflow in 2050, as pointed out in the STEPS and NZE scenarios. The combination of this trend with a lower production energy of recycled metals results in an overall decline of the embodied energy and CO₂ emissions in the oil, gas and coal infrastructures. A high recycling content of material depends on the EOL-RR of the hydrocarbon supply industry, which could be hampered by the evolution of the EOL-CR of the fossil fuels supply sector. The future of the unused infrastructures is a growing research field (e.g. OGUK [94] in the United Kingdom and Kaiser [95] in the Gulf of Mexico), and regional political decommissioning strategies will have significant impacts on the EOL-CR. Simulation of several decommissioning strategies by declines of 20% and 50% of the EOL-CR on the obsolete stock of steel are displayed in Figure 8. An estimated 0.8 billion tons of steel alloys are estimated to be accumulated in landfills or leave in-situ by 2050 in the STEPS. A decrease by half of the EOL-CR could lead to a substantial rise of this amount to almost 2 Gt by 2050. Similar results are observed in the NZE scenario, which is explained by the time-delay impact of the lifespan on end-of-life flows. The decommissioning scenarios will therefore have significant effects on the possibilities of recycling.

4.3. *Associated energy and CO₂ emissions*

The energy consumed to produce the materials increased significantly between 1950 and 2019. A domination of steel is observed in the historical and future results. It raised from 0.5 EJ to more than 1 EJ between 1950 and 2019, which represents about 0.15% of the world's primary energy demand in 2019. The energy requirements experience a slight drop to 0.96 EJ in 2050 in the STEPS and to only 0.08 EJ in the NZE scenario in 2050 (Fig. 9). This represents 0.1% of global final energy consumption in 2050 in the STEPS scenario and 0.02% in the NZE. A substantial rise is observed in the CO₂ emissions of sectoral materials production between 1950 and 2019. It evolves from 50 MtCO₂ to more than 130 MtCO₂, i.e. 0.4% of global emissions in 2019. They first peaked at more than 200 MtCO₂ in 1973, before decreasing sharply in

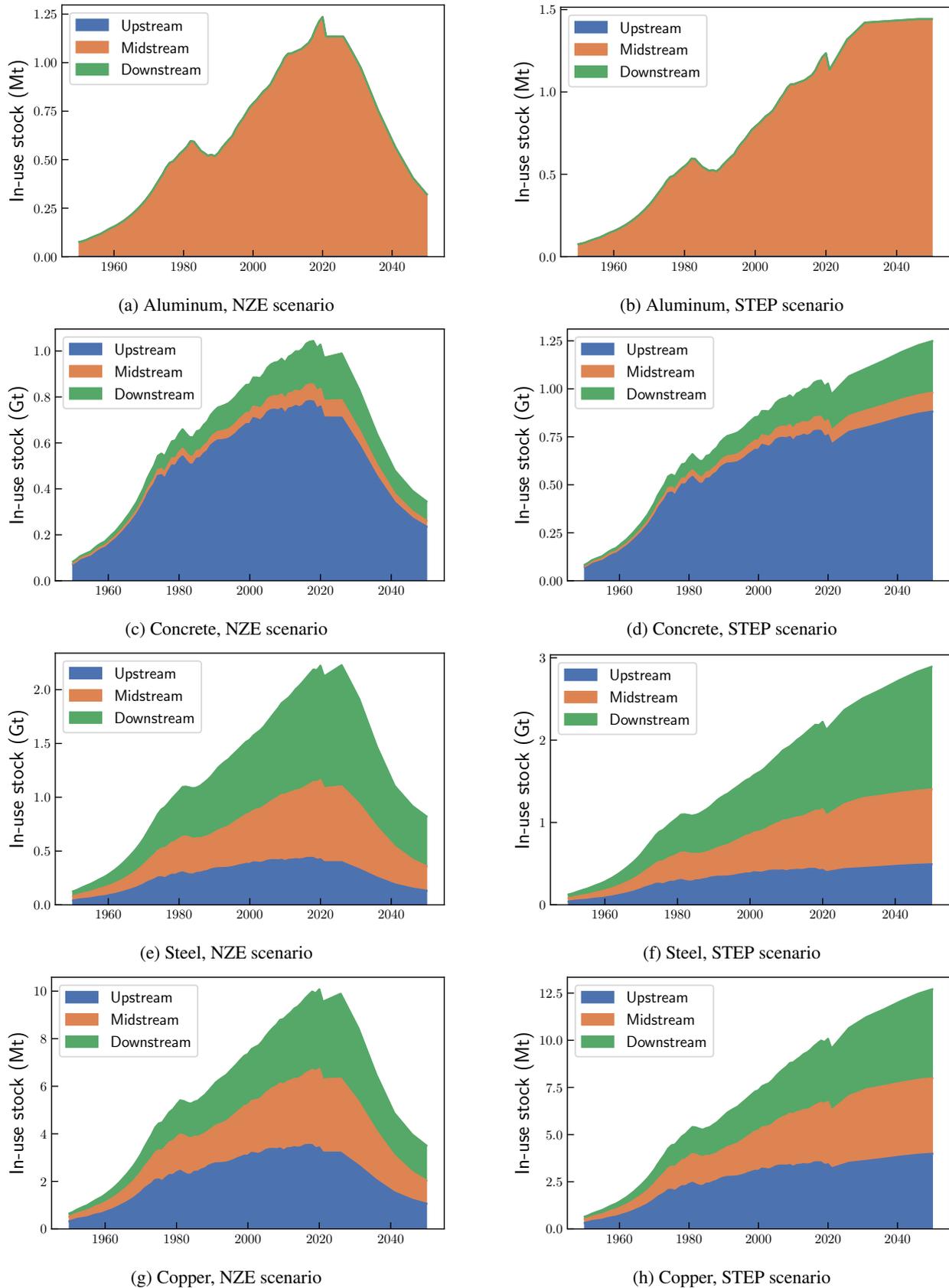


Figure 7: Historical and prospective stocks of structural materials in the NZE (left column) and STEPS (right column) scenarios.

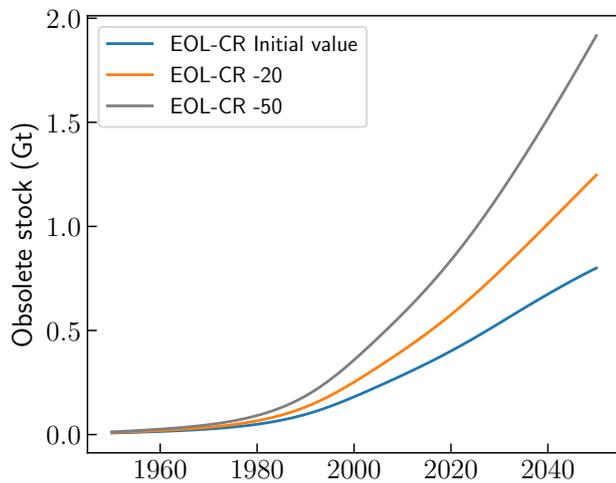


Figure 8: Obsolete steel stock in the hydrocarbon supply chain from 1950 to 2050 in the STEPS.

the 1980s. The trajectories observed in the scenarios allow for a slow decrease to 86 MtCO₂ in 2050 in the STEPS scenario and a significant drop to 25 MtCO₂ in the NZE scenario (composed only of recycling-related emissions, Fig. 9).

4.4. Sensitivity analysis

The local sensitivity analysis focuses on the mean lifetime value, for which variations of $\pm 20\%$ were computed. The results show that the materials inflows vary between -11% and +14%, and the outflows changes range from -14% to +19%. Higher impacts are observed in the outflows than on the inflows, as well as in the STEPS than in the NZE scenario.

5. Discussion

5.1. Drivers of demand and materials intensities in the fossils supply sector

The bulk materials computed in this study display different drivers. It was found that the midstream and downstream segments are the main drivers of steel, copper and aluminum demand. Conversely, the upstream segment constitutes the main consumer of concrete, ahead of the midstream activities. Those global findings can be extrapolated to national oil, gas, and coal industries. Indeed, a segmentation of countries depending on their profile (producer and/or consumer, oil, gas and/or coal) allows to estimate their materials demand pattern. A mainly consumer country is assumed to have a developed upstream segment on its domestic territory and thus a more significant share of concrete in the material demand than the global share depicted in this study. However, detailed sector data are required to accurately assess national materials demands. Sector materials intensities for the global fossils supply chain were estimated in this study (Fig. 6), and further intensities by segments were assessed (Figures S9 to S12 in the Supplementary Information). It allows for a first order evaluation of the materials consumed

per EJ of fossils produced and can be useful in future top-down materials modeling studies.

5.2. What potential for fossil fuels structures to provide materials for the energy transition?

The estimated amount of materials consumed in the hydrocarbon supply chain remains low compared to the global demand—with about 5% of the steel consumption, 1.7% of the copper and smaller share for aluminum and concrete—and to others sectors. A comparison of material intensities, annual demand, cumulative demand and in-use stock with previous studies is provided in Table 2 for both the power infrastructures and the fossil fuels supply chain. The renewable and fossil primary energy supply in scenarios considered in the studies are summarized in Table 3. The current steel demand and in-use stock estimated in this study are higher than in the power infrastructures computed by Deetman et al. [38], while concrete, copper and aluminum needs remain well below. A similar trend is observed for the in-use stocks, and an estimation of the base materials need for the fossil fuels infrastructures in SSP2 BL and SSP2 450 are provided in Table 2 for comparison basis with the results for renewable energies, grid and storage in Deetman et al. [38]. Conversely to copper, aluminum and concrete, the steel in-use stock in the fossil fuels supply chain remains twofold the amount in the renewables and power infrastructures in 2050.

Only the recycling of steel from end-of-life or decommissioned fossil fuels structures could potentially provide a significant contribution to the construction of low-carbon infrastructures. However, it will depend on both future fossil fuel and renewable supply. Relying on data scenarios and sectoral material intensities (Table 2), an estimation of the available recycled steel is provided in Table 3 and hereafter compared with the cumulative demand for the renewable technologies. An EOL-RR of 0.8 was assumed, and the actual available amounts will ultimately depend on the evolution of the collection rate, as depicted in Section 4.2.4. We observe that the increase of fossil fuels demand in the STEPS, SSP2 BL and 450 hinders any secondary steel use in the construction of low-carbon infrastructures. Conversely, moderate reduction of fossil consumption in the Blumap, 2D and B2D scenarios could allow to partially supply the cumulative steel need of the power technologies¹³. Finally, significant amounts of steel could be recycled in the WWF-Ecofys, NZE and GO scenarios, which would potentially meet the cumulative steel demand of the renewable and power storage infrastructures in the WWF-Ecofys scenario. It would only represent about 17% of the need in the GO scenario, which considers a 100% renewable energy mix. Through intensive recycling of decommissioned infrastructures, the accumulated steel stock in the fossil fuels supply chain could therefore represent an achievable means to reduce the energy and environmental toll of material use for the energy transition.

¹³Careful attention must be paid to the technological scope of each study.

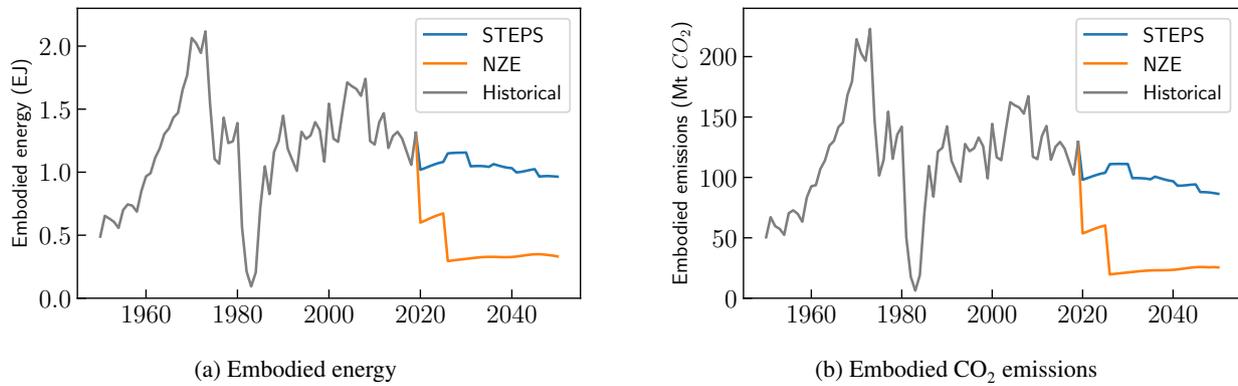


Figure 9: Embodied energy and CO₂ emissions of materials supply in the STEPS and NZE scenario.

References	Steel (iron)	Concrete	Copper	Aluminum	Years	Technologies	Scenarios
Sectoral material intensities (Mt/EJ)							
Deetman et al. [38]	5.9	54	0.4	1.5	2015	PG+G+S	Historical
This study	4	2	0.02	0.002	2015	HU+HM+HD	Historical
This study	3.8	2.5	0.023	0.006	2015	Oil	Historical
This study	9.7	3.8	0.038	0	2015	Gas	Historical
Demand (Mt/yr)							
Deetman et al. [38]	29	184	2.1	7	2015	PG+G+S	Historical
This study	79	30	0.4	0.04	2015	HU+HM+HD	Historical
Deetman et al. [38]	58	108	4.2	14	2050	PG+G+S	SSP2 BL
Deetman et al. [38]	75	227	4.9	16	2050	PG+G+S	SSP2 450
Vidal [9]	50	200	1.7	5.5	2060	R	Bluemap
Vidal [9]	600	1600	5.5	23	2060	R	GO
This study	2.3	0.2	0.01	0.005	2050	HU+HM+HD	NZE
This study	86	34	0.37	0.05	2050	HU+HM+HD	STEPS
Cumulative demand (Mt)							
Vidal et al. [57]	1,000	N/A	40	160	2000-2050	R	Bluemap
Vidal et al. [57]	12,000	N/A	200	300	2000-2050	R	GO
Månberger and Stenqvist [96]	N/A	N/A	40-170	N/A	2010-2050	R+T	B2D
Moreau et al. [59]	840	N/A	57	94	2010-2050	R+S	WWF
Moreau et al. [59]	1,500	N/A	32	46	2010-2050	R+S	2D
Moreau et al. [59]	900	N/A	78	130	2010-2050	R+S	IRENA REMAP
This study	1,000	390	4.6	0.6	2010-2050	HU+HM+HD	NZE
This study	3,200	1,300	14	1.9	2010-2050	HU+HM+HD	STEPS
In-use stock (Mt)							
Deetman et al. [38]	521	4,772	38	132	2015	PG+G+S	Historical
This study	2,000	1,000	9.3	1.1	2015	HU+HM+HD	Historical
Deetman et al. [38]	1,456	9,199	98	365	2050	PG+G+S	SSP2 BL
This study	2,880	1,390	12.6	0.77	2050	HU+HM+HD	SSP2 BL
Deetman et al. [38]	1,413	8,386	91	319	2050	PG+G+S	SSP2 450
This study	2,700	1,340	12	0.86	2050	HU+HM+HD	SSP2 450
Vidal [9]	5,000	1,200	40	120	2060	R	Bluemap
Vidal [9]	32,000	13,200	140	480	2060	R	GO
This study	820	350	3.5	0.3	2050	HU+HM+HD	NZE
This study	2,900	1,250	12.7	1.4	2050	HU+HM+HD	STEPS

Table 2

Summary of the materials intensities, demand, cumulative demand and in-use stock consumed in the power generation, storage and grid infrastructures and comparison with the hydrocarbon supply chain. PG = power generation, R = renewables, G = power grid, S = power storage, T = electric transportation, HU = hydrocarbons upstream, HM = hydrocarbons midstream, HD = hydrocarbons downstream, GO = scenario by García-Olivares et al. [97]. Value do not sum due to rounding.

Scenario	Year	Renewable supply (EJ)	Fossil supply (EJ)	Total TPES (EJ)	Estimated available recycled steel (Mt)	Reference
Historical	2015	23	370	474	N/A	IEA [98]
SSP2 BL	2050	84	694	842	0	Riahi et al. [99]
SSP2 450	2050	98	590	771	0	Riahi et al. [99]
Bluemap	2050	125	297	674	510	IEA [100]
WWF-Ecofys	2050	144	13	262	1,500	Singer et al. [101]
2D	2050	152	269	633	470	IEA [102]
B2D	2050	172	192	581	830	IEA [102]
STEP	2050	193	490	742	0	IEA [98]
IRENA REMAP	2050	222	166	494	N/A	IRENA [103]
NZE	2050	258	110	550	1,000	IEA [87]
GO	2050	389	0	389	2,000	García-Olivares et al. [97]

Table 3

Primary renewable, fossil and total energy supply in 2050 in energy transition scenarios. Bioenergy is not accounted for in the renewable supply. The available recycled steel is estimated from the steel in-use stock in 2015 and the scenarios fossil supply in 2050, assuming a 0.8 EOL-RR. GO = scenario by García-Olivares et al. [97].

5.3. The need to conduct ambitious decommissioning strategies

The significant potential of recycling materials—and especially steel—in end-of-life fossil fuels structures was identified in section 5.2. We estimated that the current in-use stock of steel could provide large amount of secondary materials to build the future renewable technologies, but that the future EOL-RR could substantially impact recycled materials availability. Two main elements could affect the EOL-RR. First, most of the copper of the fossil fuels supply chain is consumed in steel alloys (e.g. stainless steel, 7% nickel steel and 36% nickel steel in LNG infrastructures), for which down-cycling¹⁴ is frequently observed. Hayatama et al. [104] and Ciacci et al. [105] outlined the losses of copper in alloys recycling and changes in functionality of complex recycled steel alloys. Second, partial or total phasing-out of fossil fuels will require decommissioning policies. Many strategies can be adopted depending on the technology (e.g. removal, partial removal, left in place, reefing or left in place and repurposed) and will impact the EOL-RR. The removal process of the infrastructures could generate substantial energy consumption and environmental impacts [106], which if recycled—could be compared to the savings from avoiding the extraction of primary materials at a global scale in future studies.

Decommissioning remains decisive to avoid both indirect environmental impacts (e.g. preventing primary material production) and direct environmental impacts¹⁵ (e.g.

¹⁴Down-cycling is defined as the recycling resulting in a lower quality of materials, and therefore a loss of functionalities.

¹⁵The materials and environmental opportunities of decommissioning have been emphasized [107, 108].

GHG emissions of abandoned wells [109, 110, 111]¹⁶). Ambitious decommissioning policies could allow to enhance material recycling and reuse¹⁷. However, some processes will require material demand (e.g. cement plugs of oil and gas wells), a part of the estimated in-use stock will inevitably be left in place (e.g. the materials embedded in the wellbore [113]) and prohibitive collection price could hamper material recovery¹⁸. The EOL-CR will ultimately be impacted by the primary material prices and the local decommissioning policies. At a global scale, decommissioning remains at its early stage, and while some countries pave the way for ambitious policies [95, 115], other display nascent strategies [116]. However, the climate emergency urges to take rapid action to reduce the environmental toll of human activities, and ambitious decommissioning strategies could provide an additional way to increase materials recycling and reuse.

6. Robustness and limitations

6.1. Robustness criteria and local sensitivity analysis

The dynamic modeling of the hydrocarbon production and supply infrastructure stock proposed in this study represents a simple global approach to the sector, focusing on the main infrastructures. This model needs to be robust and transparent, and several robustness criteria have been identified. First, the stock modeling results are satisfactory

¹⁶Significant methane emissions have also been identified during the operational phase [112]. The study shows that large methane emissions during maintenance or failures of oil and gas equipments could represent between 8% and 12% of the sector global methane emissions.

¹⁷Davies and Hastings [111] estimated that a 16,000 tons steel jacket left in place and repurposed could retain 55,040 tCO₂eq in GHG emissions.

¹⁸Raimi et al. [114] estimated median prices for wells plugging and surface reclamation to \$76,000 in the US, with significant disparities.

for nine of the eleven infrastructure types modeled from energy production. A first category of modeled infrastructure stocks displays averaged errors of less than 10% (wells, gas and oil product pipelines, LNG liquefaction and re-gasification plants, LNG storage facilities and refineries) and a higher value are observed for coal carriers (11%), oil tankers (12%) and LNG carriers (16%). Second, the global approach developed in this study allows to assess the evolution of hydrocarbon supply chain from a minimal panel of characteristics of the hydrocarbon production and supply sector. This approach, although minimal, does allow for the analysis of the evolution of infrastructure stocks according to assumptions such as the progression of LNG or non-conventional hydrocarbons.

The sensitivity analysis conducted in this study shows moderate effects of lifetime changes. However, as previously described by Dong et al. [117] and Yin et al. [118], the time delay induced by the lifetime carries growing effects over time. A better knowledge of technological and regional values of lifetime over time is needed to prevent substantial variations in prospective dynamic modeling. It can also be noticed linear impacts of the material intensities on stocks and flows of the model. Global homogeneous data were assumed in this analysis, and a better understanding of the regional dynamics could increase the accuracy of the results. Finally, local sensitivity analysis only describes variations in a given point in space. This methodology therefore carries limitations [119], and further studies should develop global sensitivity analysis on more parameters and their possible interactions [120].

6.2. Methodology-related limitations

The hydrocarbon production and supply sector are computed independently of the other sectors, and the materials recycled are consumed in the same sector. This approach does not represent the actual recycling industry, and only a multi-sector study considering recycling as a sector would estimate accurate flows of recycled metals between the consumer sectors. In addition, the materials consumed for well closure is not considered [113], as well as the numerous decommissioning strategies (Section 5.3). The choice of a physical approach to the flows and stocks of materials also carries limitations on the effectiveness of the model in terms of operational reality of the sector. For example, an increase in concrete demand is observed in the late 2040s in the NZE scenario, despite a context of significant slowdown in hydrocarbons production. It is explained by end-of-life renewal of some infrastructures. Assumptions of life extension, well closure for profitability considerations and other sectoral and financial realities could be considered in further studies.

6.3. Data-related limitations

Most of current infrastructures data on the fossil fuels supply chain are difficult to access. To overcome this problem, the sector's players call on the services of economic intelligence companies (IHS Markit, Rystad Energy, Wood Mackenzie, etc.) which collect confidential information (obtained in an undisclosed manner) and provide data, tools and

analyses in return of a high price. Conversely, this study relies on free and online available dataset describing the evolution of the global fossil fuels supply chain over time. The dataset displayed in the Supplementary Information aims at providing global data for future studies. Further free regional data on fossil fuel infrastructures were gathered in other studies, for instance Byrnes [121]. In the present study, the data require extensive sources research, remain scarce and suffer from a lack of sources comparison and from numerous gaps, which hamper any extrapolation over time. For instance, access to reliable data over time and consistent over the geographical perimeter remains a limitation to this study. The selected data were qualified according to their geographical scope, technological scope and year of the study. The data collected do not allow a complete understanding of the complexity of the hydrocarbon production sector, due to the great variety of systems used from exploration to distribution¹⁹. Detailed data on all these technologies and their associated material intensities are not yet available, and sub-segment scale data were therefore considered²⁰. Thus, the results displayed in the study are likely an underestimate of the actual material demand. In addition, most of the data are based on European or North American devices, which could create high uncertainties in the results. This is explained by the difference in both the global hydrocarbons production and consumption patterns²¹.

Furthermore, our analysis relies on oil production scenarios which can be thrown into question. Indeed, the International Energy Agency tends to assume parameters which proved to result in too optimistic projections in the past [124, 125]. It consequently neglects the possibility to suffer from a production crunch in the coming years [126] or to experience a peak in the production of all oil liquids in the mid 2030s now envisioned by an important number of actors [127]. While the issue of credible long-term oil scenarios is critical at times of the resurgence of the 'peak oil' debate [128], it seems not to be taken into account by the IEA. We acknowledge the fact that projecting oil demand and supply is an intricate and complex task. Yet, we feel that the projections we used carry great uncertainty, and that they should be treated with a grain of salt.

7. Conclusions

This study models the evolution of the world's fossil fuel infrastructures and estimates dynamic embedded materials, energy, and CO₂ emissions from 1950 to 2050. To do so, it

¹⁹A detailed list of equipment used in the offshore production of hydrocarbons is provided by Rosneft.

²⁰For example in the exploration sub-segment, see Supplementary Information.

²¹Oil and gas drilling technologies are different from country to country, with conventional hydrocarbons requiring fewer wells drilled than unconventional hydrocarbons for an equivalent level of production. There is therefore a lack of correlation between the amount of oil produced and the number of wells drilled at the regional level, with OPEC, for example, accounting for nearly 32% of global oil production and 15% of natural gas production between 1980 and 2019 for only 2.8% of wells completed over the same period [122, 123].

firstly collects and centralizes free data from a large number of sources and thus avoids using expensive datasets from energy intelligence firms (McKenzie, IHS Markit, Rystad Energy, etc.). Without claiming to provide the same quality and disaggregation of data, our comprehensive dataset can be used by other researchers to understand the role of hydrocarbon infrastructures in the energy transition. Secondly, it develops and applies a dynamic material flow analysis (MFA).

We find that (i) the material intensities of oil, gas and coal have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption and (iii) recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll.

We furthermore highlight that the regional decommissioning strategies will significantly affect the potential of material recycling and reuse. In this context, ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures.

CRedit authorship contribution statement

Hugo Le Boulzec: Conceptualization, Methodology, Software, Data Curation, Writing - Original Draft, Writing - Review & Editing. **Louis Delannoy:** Conceptualization, Writing- Original draft preparation, Writing - Review & Editing. **Baptiste Andrieu:** Visualization, Writing - Review & Editing. **François Verzier:** Software. **Olivier Vidal:** Writing - Review & Editing, Supervision, Funding acquisition. **Sandrine Mathy:** Writing - Review & Editing, Supervision.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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