

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

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S1 Global fossil fuels supply sector data

The historical data used in this study was gathered from multiple sources, detailed in this section.

S1.1 Global historical data of the hydrocarbons supply infrastructures

The **upstream** segment is common for oil and gas, and is composed of exploration and production devices for which recent data is available. This segment includes exploration infrastructures-including devices used in seismic, magnetic and gravity methods-wells and onshore and offshore drilling rigs. At the global level, the Organization of the Petroleum Exporting Countries (OPEC) provided a census of the number of wells between 1980 and 2016 with more than 1.1 million wells in 2016 and 5,123 well pads in 2013 (OPEC, 2018). The organization also listed drilling platforms between 1982 and 2013, without distinguishing between onshore and offshore structures. However, those drilling devices are not considered in the study, because of the high level of uncertainty on the data collected. Indeed, the census of rigs remains difficult at the global level, notably due to the lack of detail in the perimeter considered in the majority of sources, and the diversity of offshore infrastructures. Baker Hughes provided a monthly report on onshore and offshore rotary rig counts worldwide, with a value of 758 rigs in June 2021¹. A value of more than 6,000 offshore oil and gas platforms are announced globally by Bull and Love (2019) and Schroeder and Love (2004), compared to 3,000 fixed offshore platforms by the IEA (2018) and more than 12,000 offshore devices by Ars and Rios (2017). However, IEA (2018) stated that the recent increase in offshore production has been partly provided by floating facilities, the number of which more than doubled between 2000 and 2016, making any accurate assessment of offshore production devices difficult. Adding to this difficulty of identification is a trend toward larger platforms, greatly complicating modeling from fossil fuel generation. IEA (2018) stated that the size of platforms increases over time, allowing production to be maintained while decreasing their number. Conversely, no census of the equipment used in exploration methods has been obtained, but a study listing the quantities of raw

¹Baker Hughes proposes a [monthly inventory](#) of the global active rigs.

materials consumed has been produced by the American Petroleum Institute (Steiniger, 1962). Finally, the coal mines have been separated into two underground and opencast categories. It is estimated that 40% of coal production comes from surface mines and 60% from underground mines (World Coal Institute, 2009), with various extraction equipment.

In contrast to upstream, the activities of the **midstream** segment are different for oil and gas, especially for processing. While oil does not require processing, several steps are required before eventual gas transportation and then distribution. Schori (2012) further stated that the extent of processing depends on the quality of the gas produced. The processed gas and oil are then transported to consumption centers. Four methods of transportation exist: road, rail, sea, and pipeline. Only the last two are modeled here. Only 20% of gas is traded on international markets and not consumed regionally. Similarly, in 2015, 61% of the transportation of petroleum products was by sea lanes (EIA, 2017). For natural gas, pipeline transportation and marine transportation in liquefied form were therefore considered in this study. It includes the liquefaction of natural gas, its transport in the form of liquefied natural gas (LNG) in LNG tankers, and its regasification. The market share of LNG has strongly increased over the recent decades, with global liquefaction capacity growing from 165 bcm in 2000 to more than 467 bcm in 2017, while regasification capacity has evolved from 334 bcm to more than 1,138 bcm in the same period (ENI, 2018). Similarly, the evolution of the number of LNG carriers since the late 1960s - the years of construction of the first ships - follows a strong growth, linked to the rapid development of LNG globally. IGU (2018) detailed a growth to about 200 ships in 2000, eventually progressing to 525 units in 2018. The liquefaction of gas allows storage. Over the past decades, LNG global storage capacity have increased from 39 mmcm to 62.8 mmcm between 2011 and 2018² (IGU, 2018). Gas pipelines represent the second main way of transportation of natural gas. The network of natural gas transmission and distribution pipelines has grown considerably over the last two decades. Its length was estimated at more than 844,000 kilometers in 2000, finally evolving to 3.04 million kilometers in 2017 (CIA, 2019). However, these data do not agree with the estimates of CEER (2018), announcing more than 1.9 million kilometers for the European network, compared to only 224,000 km for CIA (2019). We can also identify a strong difference for the French case, with 195,000 km of gas pipeline network announced by the French Ministry of Ecological Transition (2022), against about 15,000 km for CIA (2019), as well as for Canada, with more than 450,000 km of gas pipelines NRCAN (2020) against 110,000 km for CIA (2019), and finally the United States, with 1.9 million kilometers announced by CIA (2019), lower than the 2.3 million kilometers identified by PHMSA (2022). These differences stem from the scope of the studies considered. Pipelines can be separated into three broad categories: transmission pipelines, carrying hydrocarbons over long distances from production centers, distribution pipelines, serving end-users over short distances, and gathering pipelines, used between the field and the transmission system (Moureau and Brace, 1993). However, the latter network remains a minority, accounting for only 0.7% of the U.S. gas network in 2018 (PHMSA, 2022). Using data for the European, US, and Canadian gas networks, we estimated a distribution pipeline share of 85% of the pipeline network. The rate was applied to the data on the gas transmission pipeline network provided by CIA (2019), allowing us to obtain the historical evolution of the global network between 2000 and 2017. In this study, the transportation network evolved from 840,000 km to more than 1.36 million km between 2000 and 2018. For petroleum products, the midstream segment includes both tankers, transport and distribution pipelines, and storage infrastructure. Globally, tanker transport grew strongly between 1980 and 2018, from 388 million Dead Weight Tons (MDWT) to 561 MDWT, for about 12,000 units (UNCTAD, 2018; GIGNL, 2019). Tanker transport can be considered "dynamic" storage, but is not considered as such here to avoid double counting. Geological storage was also excluded, due to lack of raw material data. Finally, only man-made "static" storage tanks have been considered here. These are estimated at 8 billion barrels, more than half of which are in OECD countries, including both commercial and strategic stocks (Magazine, 2016; IEA, 2018; OPEC, 2018). Finally, in contrast to the natural gas pipeline network, the petroleum product pipeline network has seen little growth between 2000 and 2018, with the length increasing from 584,000 km to 788,000 km (CIA, 2019). The data considered do not suffer from the same drawback, as the global network is predominantly a transportation network, not a distribution network, unlike the gas network. For coal, the midstream segment remains simpler. After extraction, coal can be processed before being transported, in order to

²The storage capacity is measured in).

meet customers' requirements. This is accomplished by crushing it, separating it by size, and then purifying it of mineral matter (Miller, 2017).

The final segment of the hydrocarbon supply chain is the **downstream**, which gathers refining and distribution activities. Refining capacity has increased significantly between 1965 and 2017, from 34.8 to more than 98 million barrels per day with more than 600 refineries worldwide (BP, 2021; OGI, 2009, 2014). In the absence of data on the share of transmission and distribution networks, the entire petroleum product network was considered a transmission network. The gas network is 86% a distribution network, and its length has increased from 4.4 to over 10 million kilometers between 2000 and 2018 (CEER, 2018; CIA, 2019; NRCAN, 2020; PHMSA, 2022).

S1.2 Recent evolution of the oil, gas and coal sectoral production structure

Several developments in the oil and gas sector have been taken into account in this study. As mentioned above, an increase in the share of gas transported in the form of Liquefied Natural Gas (LNG) has been considered, as well as the share of unconventional oil and gas. Unconventional production has been separated into two main categories with different characteristics: oil sands and shale oil on the one hand, shale gas and tight gas on the other. Since oil sands exploitation does not require drilling, only the second category was considered. In order to model the impact of the increase in production of unconventional hydrocarbons, three factors were considered: a decrease in the lifespan of the wells, a decrease in their depth, and an increase in their number.

For the same level of production, more unconventional wells are needed, which is explained from the production profile of unconventional drilling, measured by the production decline rate. It is defined as the annual rate of reduction in oil or gas production from an oil field, and is calculated for each well and at the aggregate level. It differs according to the age of the well, but also between conventional and unconventional hydrocarbons, for which its value is higher (Kleinberg et al., 2018). The average value of the production reduction rate is about 2% to 8% for conventional hydrocarbons (IEA, 2019; Michaux, 2019; Höök et al., 2009). The rate fluctuates depending on the size of the oil field, its geographical location and its physical situation-offshore or onshore (Höök et al., 2009; IEA, 2013). The values observed for fields producing unconventional hydrocarbons are considerably higher. In the Bakken field, located in the United States, this rate reached nearly 60% in the first year of production, and then 25% in the second year (IHS, 2013), while the Barnett field experienced a rate of 39% after 2 years, eventually reaching 95% over 10 years (Stevens, 2010), and the Eagle Ford field experienced a reduction of 74%, 47%, and 19%, respectively for the first, second, and third year of production (Wachtmeister et al., 2017). This hyperbolic pattern of production reduction therefore explains the need to increase drilling in order to maintain a high level of production. The density of wells per square kilometer, however, varies considerably by reservoir, by hydrocarbon type, and by data source. Komduur (2010) announced a density of 12 wells per km² in the Barnett oil field in the United States, compared to 2 wells per km² according to the EIA (2013). At the national level, the EIA (2013) provided the density of wells in the large unconventional American fields, ranging from 0.4 to 6 wells per km² with an average value of 2.8 wells per km², which is still higher than the largest conventional fields in the world for which the values vary between 0.07 and 8.9 wells per km². Because of this large disparity, no difference in well density was retained in this study.

In addition to a change in well density, a decrease in well life is observed. Indeed, the production reduction rates allow us to estimate a lifetime of unconventional hydrocarbon wells between 8 and 12 years, compared to 30 to 40 years for conventional hydrocarbon production (Stevens, 2010). Finally, the increase in the share of unconventional hydrocarbons and deepwater drilling changes the average depth of drilling. The horizontal drilling technique increases the total length of the wells, composed of a vertical part and then a horizontal part. The first part of the drilling consists of the vertical part of the well, in the same way as conventional hydrocarbons. Newell et al. (2016) announced an average vertical depth between 1,200 and 3,900 meters, while Zendejboudi and Bahadori (2017) between 1,000 and 3,000 meters. This value reaches an average of 1828 meters in the Marcellus Basin (Fractracker, 2022). Once the reservoir depth is reached, horizontal drilling begins. On the Marcellus Basin, located in the United States, the average length of this second portion was 1150 meters

between 2006 and 2016, and an increase in the length of the horizontal portion of drilling over time (Doak et al., 2019). The average horizontal drilling distance in the Marcellus Basin increased from 690 meters in 2003 to 1,200 meters in 2013, and to 3,000 meters in 2018. Nationally, this distance has evolved from 1547 meters in 2012 to 2,221 meters in 2018 (Hughes, 2019), for a total drilling length of approximately 4,000 meters in unconventional wells in the United States. This evolution can be seen in the distribution profile of drilling in Canada and the United States, with a sharp increase in the proportion of drilling to a depth of around 2,000 meters, and the appearance of drilling to a depth of over 5,000 meters. The average depth of drilling in the United States has increased from 1,100 meters in 1950 to more than 1,700 meters in 2008. Finally, the characteristics retained are an average drilling length of 1,500 meters and a life span of 40 years for conventional deposits and 4,000 meters and 12 years for non-conventional deposits.

S2 Embodied energy and CO₂ emissions

The embodied energies of primary and secondary materials considered in this study 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 (Norgate et al., 2007; Birat et al., 2013; Gutowski et al., 2013; Vidal, 2021). Data from Vidal (2021) are considered for copper, aluminum, and steel. The values considered for steel are used for all steel alloys in this study. Cement and concrete production is decentralized, so material intensities depend on the efficiency of regional production facilities. Numerous cement and concrete material intensities are proposed in the literature, both globally (Van den Heede and De Belie, 2012; Birat et al., 2013) and by region (Marinković et al., 2017; Goggins et al., 2010; Praseeda et al., 2015)³. Because of this decentralization, a multi-regional approach is adopted to estimate a global cement material intensity. In this study, we have assumed an identical intensity for clinker and cement, theoretically composed of 95% cement (Taylor et al., 2006). In order to simplify the calculations, only the main producing areas have been considered. China, India, Europe, the United States and Japan represent nearly 70% of the world cement production between 1956 and 2016 (USGS, 2021), so regional energy intensities were determined for these regions using historical data and a logistic approach. For this purpose, a theoretical energy intensity limit for cement was set at 1.76 MJ/kg (Worrell et al., 2001; Taylor et al., 2006) and a maximum intensity of 20 MJ/kg. This value remains uncertain but has little impact on the study since 96.7% of cement produced since 1900 was manufactured after 1950, and nearly 90% after 1970 (USGS, 2021). Regional energy intensities are then weighted by regional cement production, yielding a global cement/clinker intensity. Historical data for regional shares of global production are obtained between 1956 and 2016 (USGS, 2021). The observed 1956 distribution is assumed constant since 1950, and the 2016 distribution is assumed constant through 2100. Cement/clinker energy intensity thus varies annually between 1900 and 2100 ?? according to the combined change in regional energy intensities and regional market shares in world production.

Recycling reduces the energy required for the production of materials, due to the lower number of stages in the production of secondary metals than in primary metals. Indeed, primary production involves steps such as mining and mineral processing (for copper, nickel, zinc, lead...) or crushing and screening for steel (Norgate et al., 2007; Chen et al., 2019), which are not mobilized during secondary production. Secondary production primarily involves scrap smelting and refining, as well as several steps of collection, recovery sorting and shredding (Norgate, 2013). Schäfer and Schmidt (2019) and Johnson et al. (2007) pointed out that the origin of the metals collected influences the energy required for their recycling, and report embodied energy of secondary copper sometimes of the same order of magnitude as that of primary copper. The scope of secondary metals production thus includes processes from collection to refining. In this study, the embodied energy of secondary metals is assessed from a literature review of the energy typically consumed in secondary processes, either in absolute terms or in terms of the energy consumption of primary processes. However, this proportion of primary

³Many other studies provide regional cement and concrete intensities. A non exhaustive list of them include : Alcorn and Wood (1998); Hammond and Jones (2008); Baird (1997); Kofoworola and Gheewala (2009); Dias and Pooliyadda (2004); Scheuer et al. (2003); Debnath et al. (1995); Wan Omar et al. (2014); Dixit (2017); Worrell et al. (2001, 1994); Praseeda et al. (2017); Li et al. (2015); Gervasio et al. (2018); Lu et al. (2009); Mack (2015); Taylor et al. (2006)

production consumption varies considerably over time as the ore grade changes (Norgate and Jahanshahi, 2006). The proportion estimated in this study is therefore valid only for the current period. This makes it possible to estimate a world average consumption of secondary metals, varying then according to an annual rate of technological improvement of 1% between 1900 and 2100. Only steel, aluminum and copper are considered in the secondary production. Nearly 70% of steel is currently produced by the Blast Furnace/Basic Oxygen Furnace (BF/BOF) process and 30% via Electric Arc Furnace (EAF), with large regional disparities (Yellishetty et al., 2010). EAF route steel represents most of the secondary steel production, explaining this heterogeneity. This route allows secondary steel to consume between 1.3 and 6 GJ/t currently (Harvey, 2021), 2.6 MJ/kg according to Norgate (2013), 4.5 MJ/kg in Europe according to Birat et al. (2013) and decreasing from 8.8 MJ/kg in 2010 for the United Kingdom (Hammond and Jones, 2008) and 7 MJ/kg at the end of the 1990s for the most energy efficient processes (de Beer et al., 1998). Secondary steel thus consumes between 8 and 37% of the primary production energy depending on the source. A current value of 20% is chosen, in agreement with the most recent sources, i.e. 3.5 MJ/kg for the metallurgical processes. After adding the energy needed for collection, recovery, sorting and shredding, the final value of embodied energy of 3.9 MJ/kg is finally considered⁴.

Aluminum has a more drastic decrease of the energy consumption necessary for its production thanks to recycling⁵. It reaches between 5 MJ/kg and 8.9 MJ/kg (Kear et al., 2000; Quinkertz et al., 2001; Schifo and Radia, 2004; Green, 2007; Birat et al., 2013; Norgate, 2013; Milford et al., 2011), which represents a proportion of the primary production energy mostly between 5% and 10%, and reaching up to 13%. A current proportion of 7% was selected based on a weighting according to the age of the sources, allowing to estimate an average embodied energy value of secondary aluminum of 5.1 MJ/kg for metallurgy, and a final value of 5.6 MJ/kg. Secondary copper production is achieved depending on the origin of the copper scrap, either through the pyrometallurgical process or the hydrometallurgical process, especially for printed circuit boards (Xu et al., 2016). No works studying the embodied energy of secondary copper at the global level have been found. At the Chinese level, Chen et al. (2019) proposed a quantification of each stage of primary and secondary production, and arrive at a proportion of 21% of secondary copper embodied energy to primary. A similar proportion is estimated by Gaines (1980), with 20% on the US perimeter. Presenting differences according to the ore concentration rate, Norgate and Jahanshahi (2006) reported a share of smelting and refining of only 9% for copper mined with a concentration of 0.5%, reaching 40% for 3% Cu. A world average value of 15% is finally retained, i.e. 11.6 MJ/kg for the metallurgical process, and 12.8 MJ/kg for the final embodied energy value of secondary copper.

⁴This value depends on the distance traveled for between the collection site and the recycling site (Norgate, 2013). A distance of 150 km was considered in this study. The strong impact of transport on recycling was also considered by Barba-Gutiérrez et al. (2008)

⁵Salonitis et al. (2019) provided a breakdown of energy consumption by primary production stage.

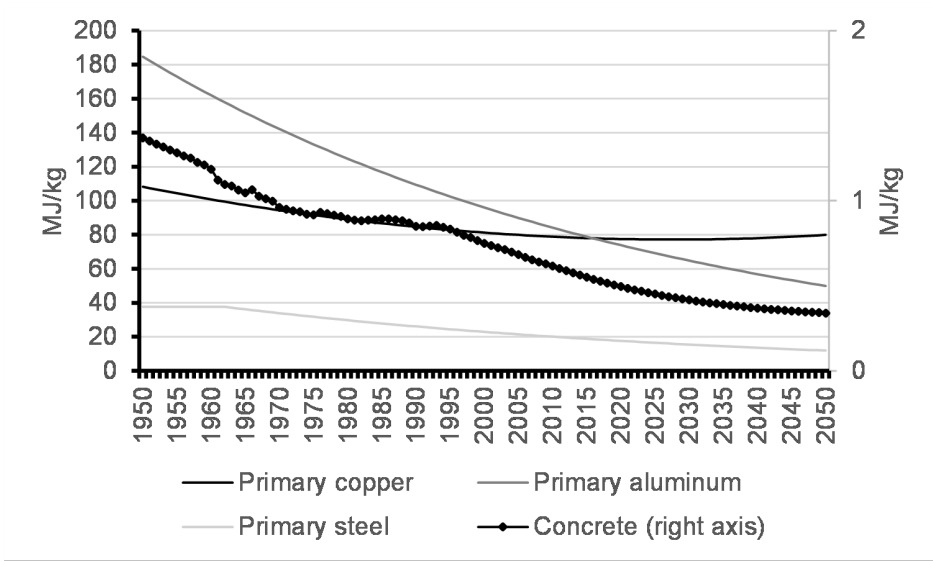


Figure S1: Embodied energy of the primary materials production.

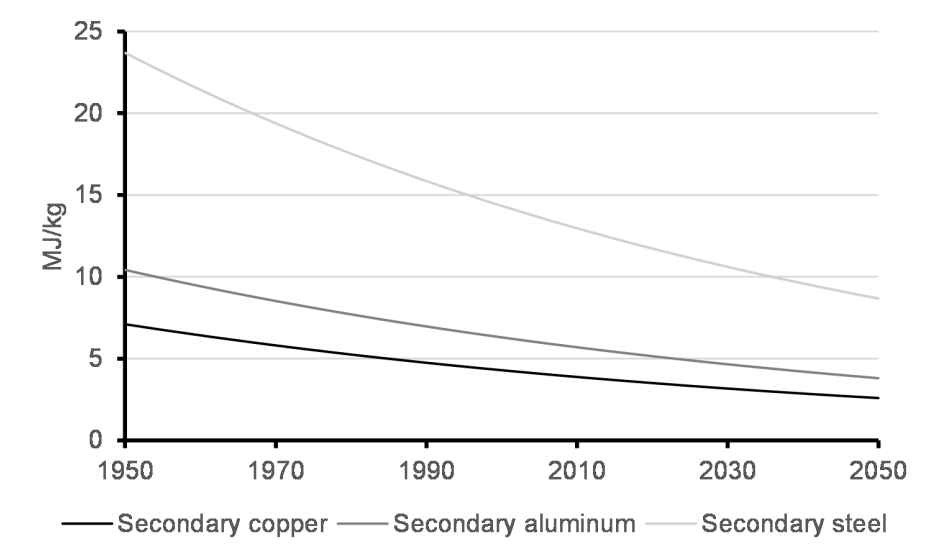
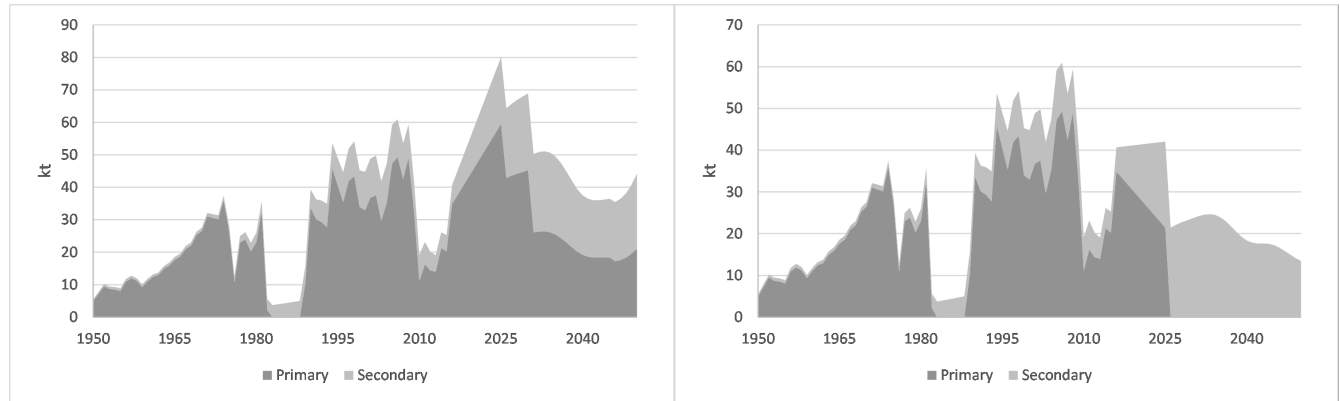


Figure S2: Embodied energy of the secondary materials production.

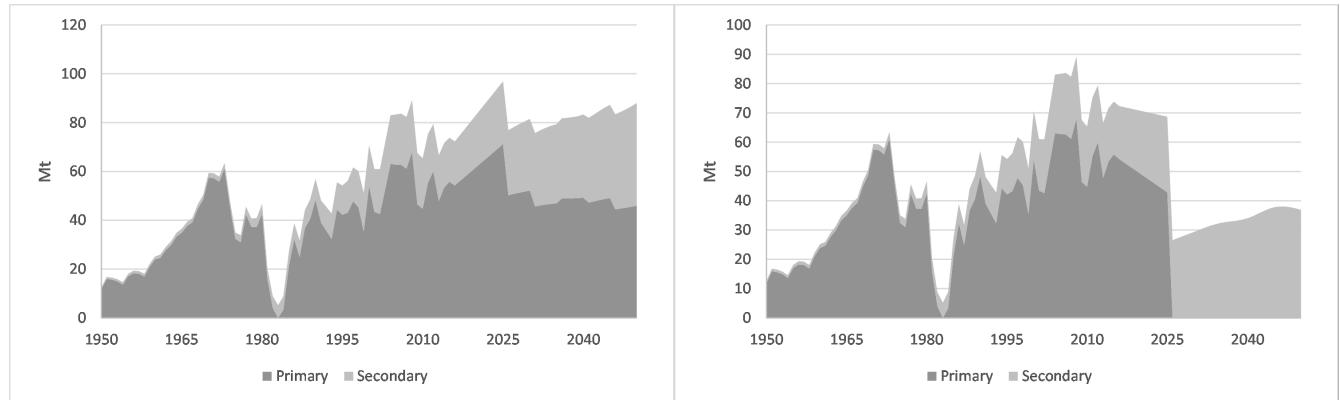
S3 Materials, energy and CO₂ : further results

S3.1 Bulk materials primary and secondary flows in the STEP and NZE scenarios

The bulk materials primary and secondary flows are presented in this section for the two considered scenarios.



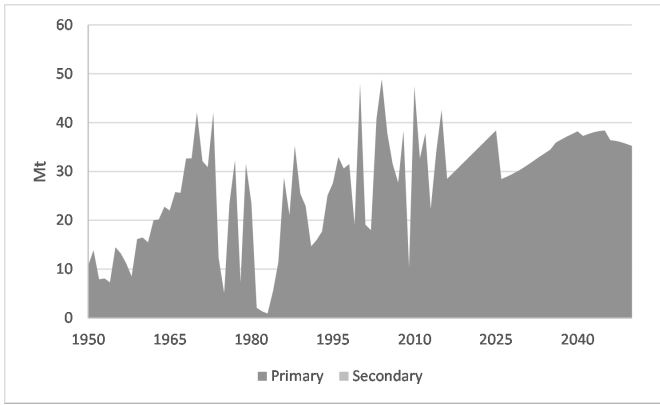
(a) Aluminum primary and secondary flows in the STEPS scenario. (b) Aluminum primary and secondary flows in the NZE scenario.



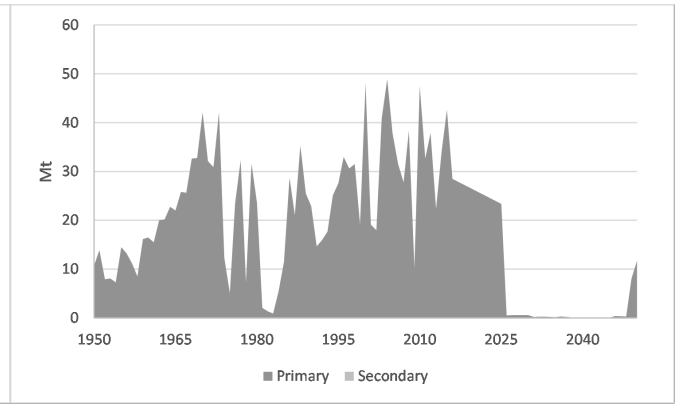
(c) Steel primary and secondary flows in the STEPS scenario.

(d) Steel primary and secondary flows in the NZE scenario.

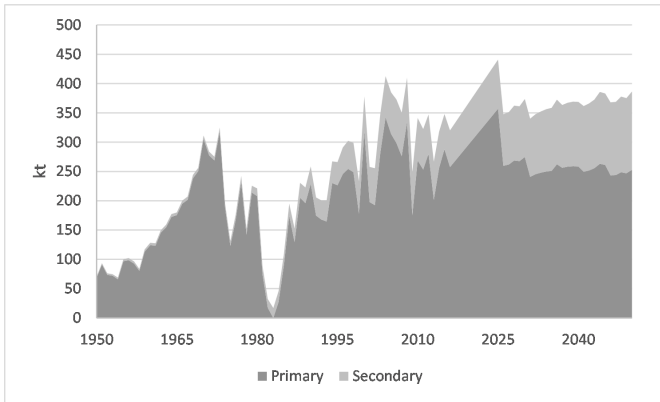
Figure S3: Aluminum and steel primary and secondary flows in the fossil fuels supply sector for the NZE and STEPS scenarios.



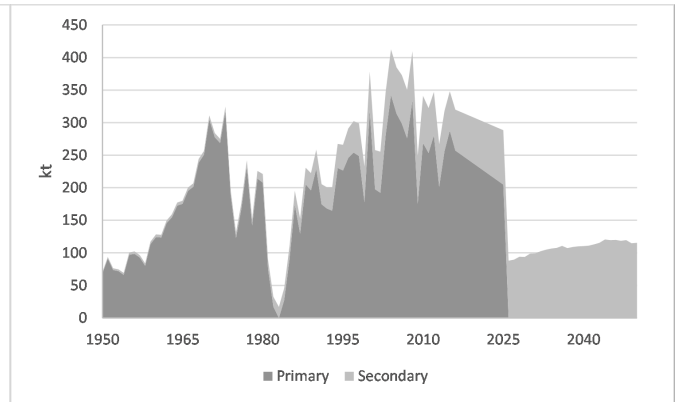
(a) Concrete primary and secondary flows in the STEPS scenario.



(b) Concrete primary and secondary flows in the NZE scenario.

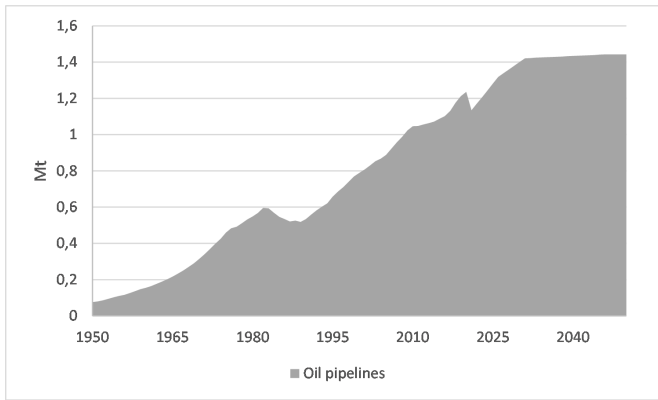


(c) Copper primary and secondary flows in the STEPS scenario.

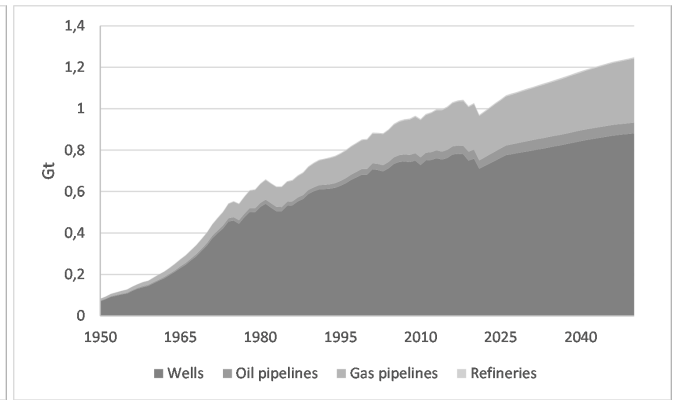


(d) Copper primary and secondary flows in the NZE scenario.

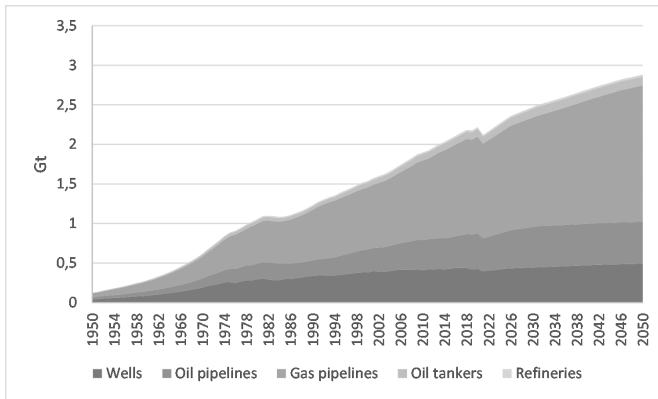
Figure S4: Concrete and copper primary and secondary flows in the fossil fuels supply sector for the NZE and STEPS scenarios.



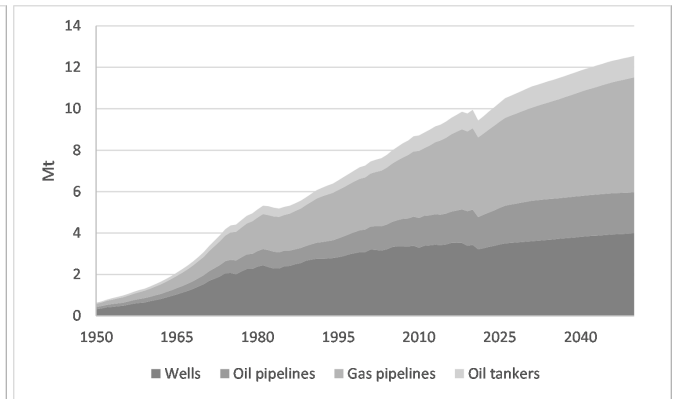
(a) Aluminum.



(b) Concrete.

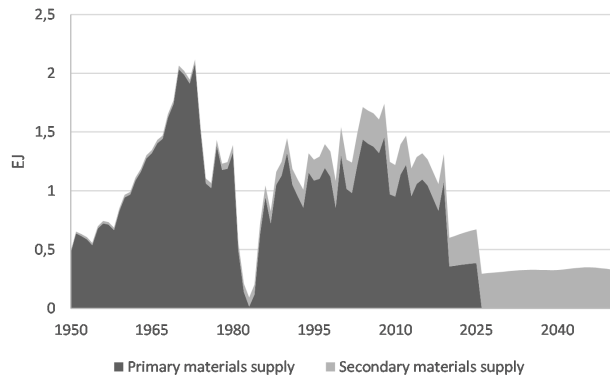


(c) Steel.

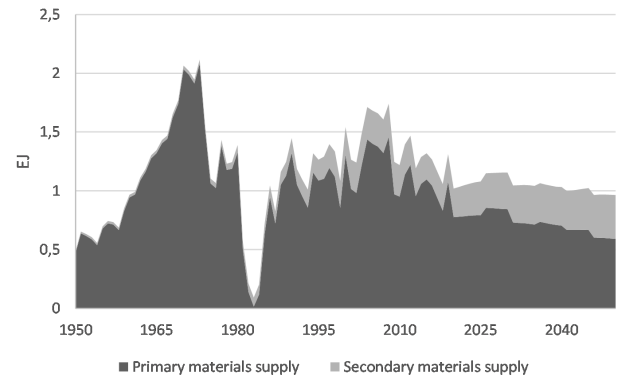


(d) Copper.

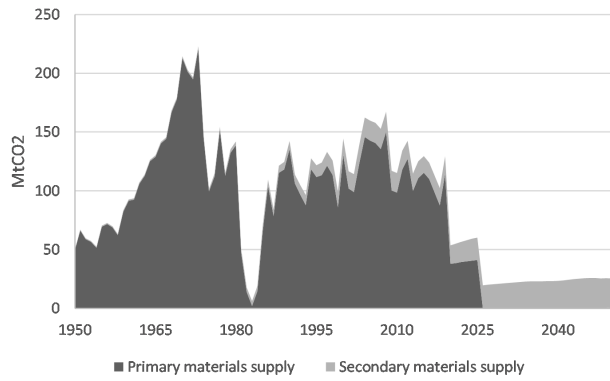
Figure S5: Structural materials stocks by main consuming infrastructures in the STEPS scenario.



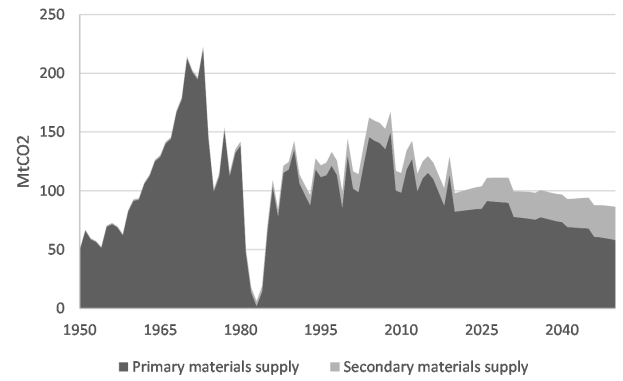
(a) Embodied energy of materials supply in the NZE scenario.



(b) Embodied energy of materials supply in the STEPS scenario.



(c) Embodied CO₂ of materials supply in the NZE scenario.



(d) Embodied CO₂ of materials supply in the STEPS scenario.

Figure S6: Embodied energy and CO₂ of materials supply by segments in the STEP and NZE scenarios.

S3.2 Historical sectoral materials intensities in the fossils supply sector

References	Steel (<i>iron</i>)	Concrete	Copper	Aluminum	Years	Technologies	Scenarios
Sectoral material intensities (Mt/EJ)							
Deetman et al. (2021)	5.9	54	0.4	1.5	2015	PG+G+S	Historical
Deetman et al. (2021)	3.9	50	0.3	0	2015	PG	Historical
Deetman et al. (2021)	2	4	0.1	1.5	2015	G	Historical
This study	4	2	0.02	0.002	2015	HU+HM+HD	Historical
This study	0.8	1.5	0.007	0	2015	HU	Historical
This study	1.3	0.1	0.006	0.002	2015	HM	Historical
This study	1.9	0.4	0.006	0	2015	HD	Historical

Table S1: Summary of the materials intensities in the power generation, storage and grid infrastructures and comparison with the hydrocarbons 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. Value do not sum due to rounding.

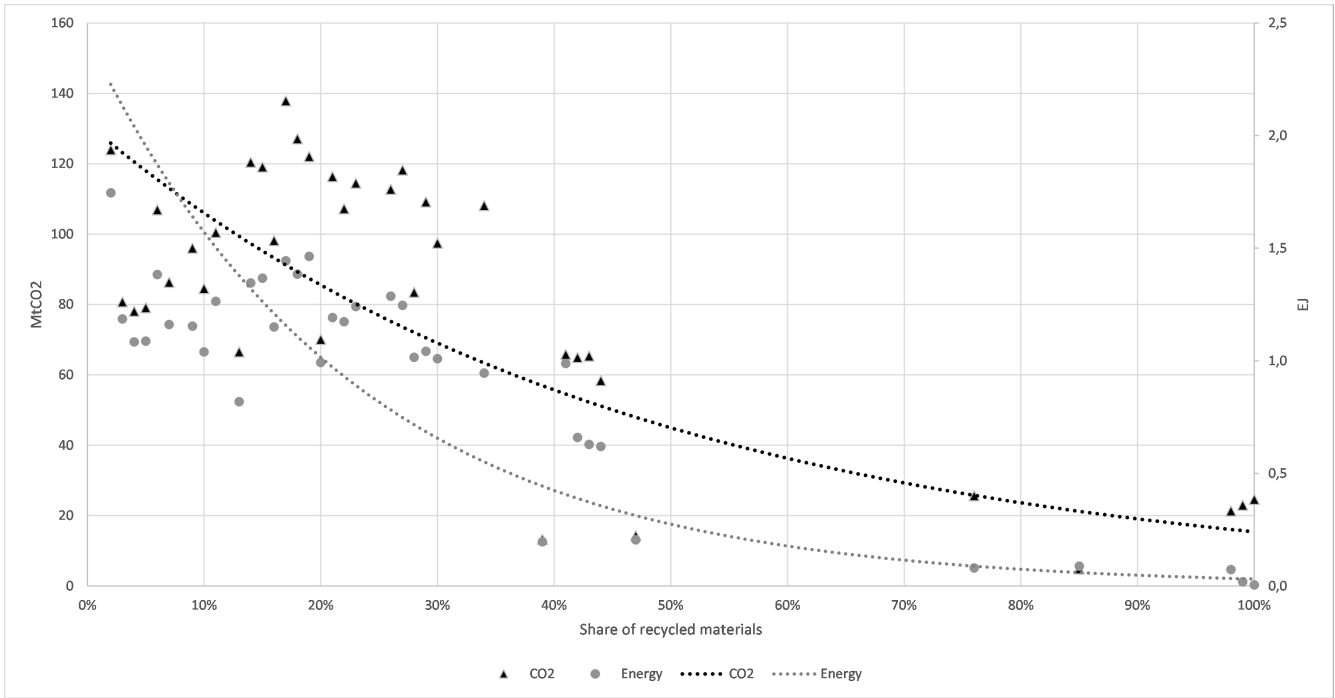
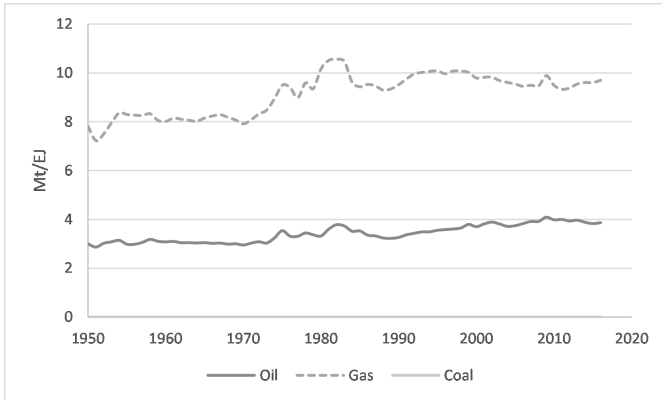
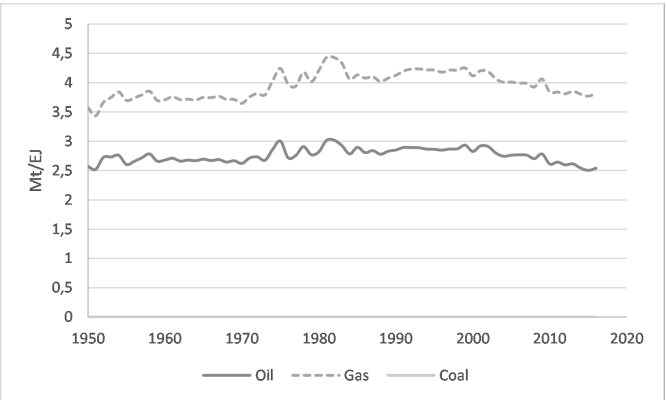


Figure S7: Evolution of embodied CO₂ emissions and embodied energy consumption depending on the share of recycled materials in the demand.

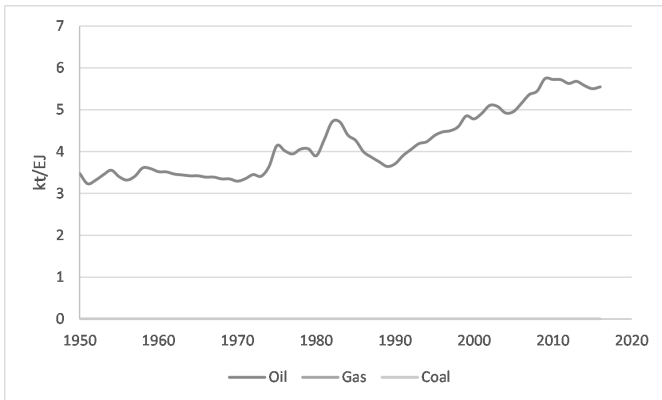
S3.2.1 Historical sectoral materials intensities by hydrocarbons in the fossils supply sector



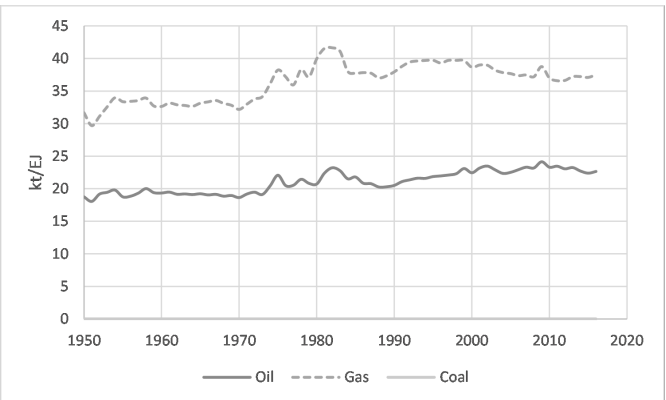
(a) Historical steel materials intensities by hydrocarbon.



(b) Historical concrete materials intensities by hydrocarbon.



(c) Historical aluminum materials intensities by hydrocarbon.



(d) Historical copper materials intensities by hydrocarbon.

S3.2.2 Historical sectoral materials intensities by segment in the fossils supply sector

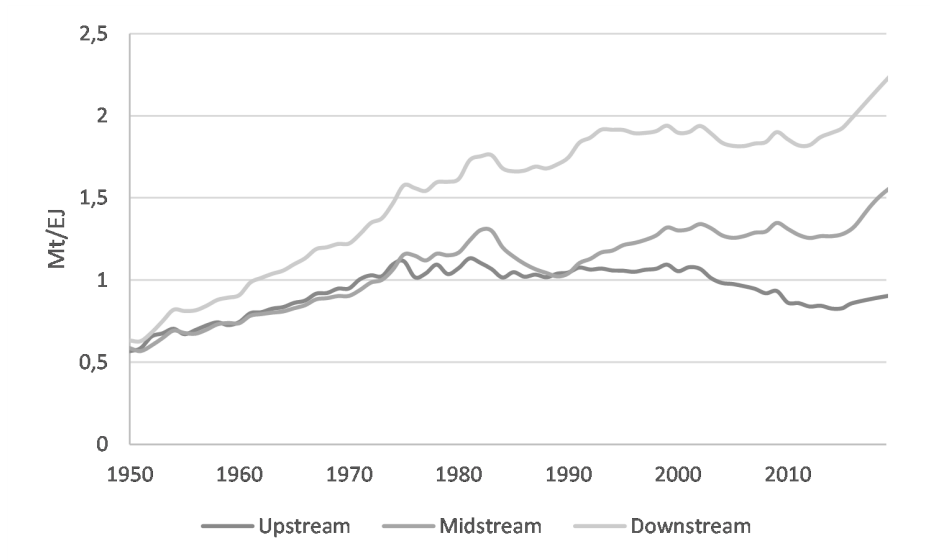


Figure S9: Historical steel materials intensities by segment.

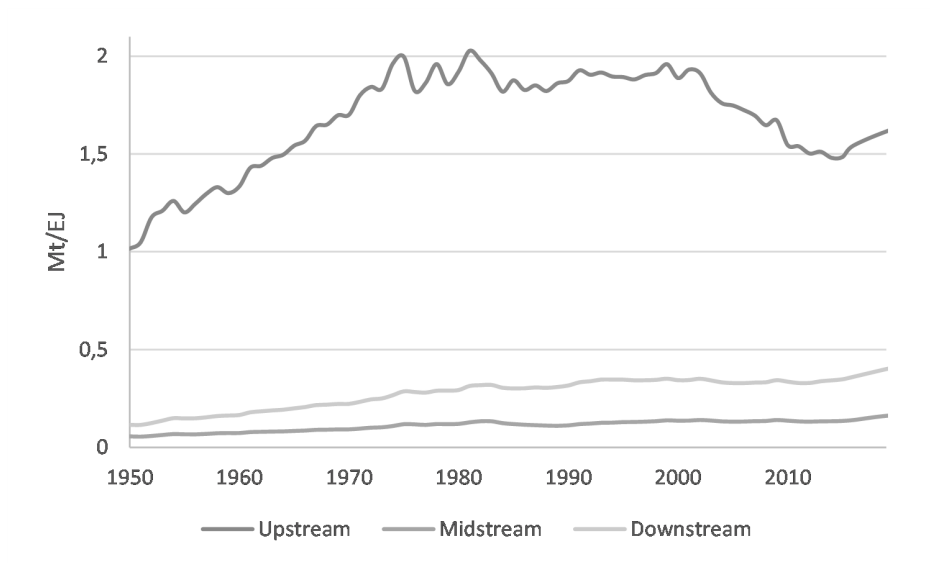


Figure S10: Historical concrete materials intensities by segment.

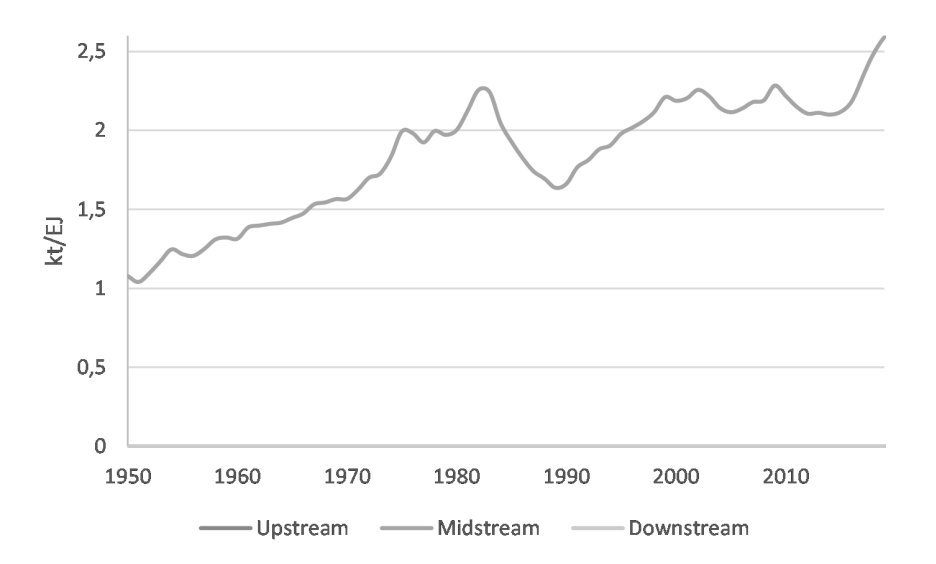


Figure S11: Historical aluminum materials intensities by segment.

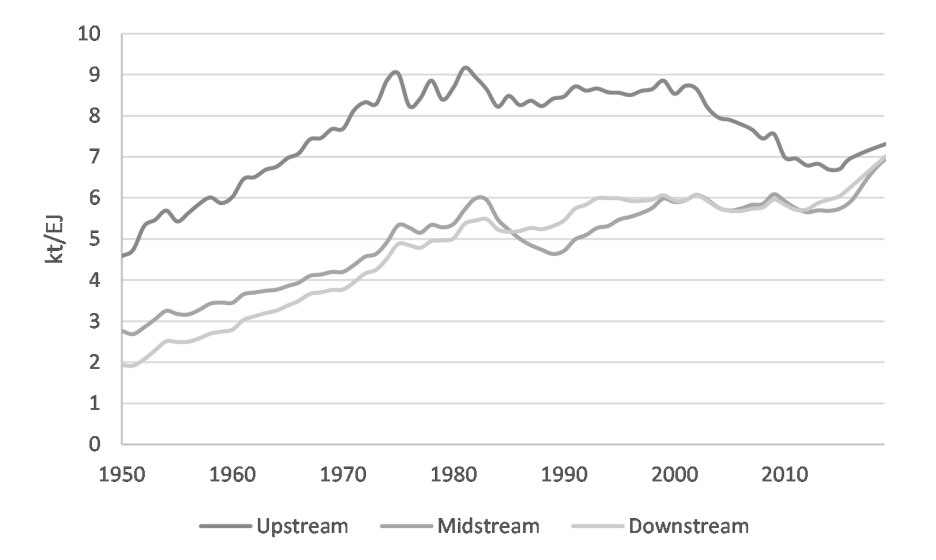


Figure S12: Historical copper materials intensities by segment.

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