CEH CENTER for ENVIRONMENTAL HEALTH

Flooring's Dirty Climate Secret

Quantifying Carbon Dioxide Emissions and Toxic Chemicals Used in Vinyl Flooring Manufacturing

Authors

Autocase Economic Advisory is comprised of a team of professional economists that conduct rigorous, evidence-based economic analyses of the financial, social, and environmental costs and benefits of climate adaptation, sustainability and resilience investments in the infrastructure, real estate, public policy, and regulatory worlds. We have developed best-practice economic analysis approaches and have been involved in all facets of infrastructure including climate vulnerability, mitigation, adaptation, and planning. Our economic analyses help clients prioritize investments, understand risks, develop strategic plans, report Environmental, Social, and Governance (ESG) metrics, secure funding, communicate with stakeholders, support climate equity, and understand the holistic trade-offs of investments and policies. We have built the market-leading cloud-based automated economic business case software, Autocase, with modules for evaluating high performance buildings and green infrastructure. In aggregate, our team's track record conducting economic assessments to inform decision making spans roughly $100 billion USD of projects. Autocase is also an Institute for Sustainable Infrastructure (ISI) Charter Member, an Envision Qualified Company, and a 100 Resilient Cities (Rockefeller Foundation) Platform Partner.

Center for Environmental Health is a nonprofit organization devoted towards protecting people from toxic chemicals by working with communities, consumers, workers, government, and the private sector to demand and support business practices that are safe for public health and the environment. We are dedicated to putting the health of families back in their own hands by working for these groups to reduce the use of environmentally harmful products and major toxics from everyday products. Dr. Jimena Diaz Leiva is Science Director at the Center for Environmental Health, Rachael Wein is the Director of the Built Environment Program, Judy Levin is Senior Advisor to the program, and Malena Spar is the Program Manager.

Material Research L3C, is an international partnership of researchers specializing in the environment, public health, and social justice. Jim Vallette, President, is the lead author of an extensive catalog of PVC related reports, including Chlorine and Building Materials: A Global Inventory of Production Technologies, Markets, and Pollution (two parts, released in 2018 and 2019), Post-Consumer Polyvinyl Chloride in Building Products (2015), The New Coal: Plastics and Climate Change (2021) and co-author of Chemical Hazards Analysis of Resilient Flooring for Healthcare (2010).

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Glossary

ATSDR - Agency for Toxic Substances and Disease Registry
BAT - Best Available Techniques
CCWG - Clean Cargo Working Group
CO_2e - Carbon Dioxide Equivalents
DEHP - Di-2-Ethylhexyl Phthalate
ECCC - Environment and Climate Change Canada
EDC - Ethylene Dichloride
eGRID - Emissions & Generation Resource Integrated Database
EIA - Economic Impact Analysis
EPA - Environmental Protection Agency
EPD - Environmental Product Declaration
EPDLA - European Polymer Dispersion and Latex Association
ESG - Environmental, Social, and Governance
FLIGHT - Facility Level Information on GreenHouse gases Tool
GREET - Greenhouse gases, Regulated Emissions, and Energy use in Technologies
HBN - Healthy Building Network
$HgCl_2$ - Mercuric Chloride
HPD - Health Product Declaration
ICIS - Independent Commodity Intelligence Services
IEA - International Energy Agency
IRIS - Integrated Risk Information System
ISI - Institute for Sustainable Infrastructure
LCA - Life Cycle Analysis
LCCA - Life Cycle Cost Analysis
LVT - Luxury Vinyl Tile
MCDA - Multi Criteria Decision Analysis
PFAS - Per- and polyfluoroalkyl substances
PTFE - Polytetrafluoroethylene
PVC - Polyvinyl chloride
TBL-CBA - Triple Bottom Line-Cost Benefit Analysis
TEU - Twenty-foot Equivalent Unit
TRACI - Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
UNEP - United Nations Environment Programme
USGS - United States Geological Survey
VCM - Vinyl Chloride Monomer
VOC - Volatile Organic Compound
WARM - Waste Reduction Model
WHO - World Health Organization

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Key Findings

1. Manufacturer Environmental Product Declarations (EPDs) underestimate the carbon dioxide emissions from producing polyvinyl chloride (PVC) flooring by between 8 and 180%.

Environmental Product Declarations (EPDs) (RFCI, 2019) undercount the estimated carbon dioxide equivalent emissions from the production of vinyl tile flooring sold in the U.S. market by **27%** for floors with PVC resins made in the U.S., and **171%** for floors with resins made in China. For vinyl sheet flooring, EPDs undercount the carbon dioxide equivalent emissions by **8%** for floors with PVC resins made in the U.S., and **180%** for floors with resins made in China.

Manufacturer EPDs (RFCI, 2019) draw from limited and outdated data and rely on estimates from one production plant based in the U.S. (Franklin and Associates, 2003). Key differences in the carbon feedstock used to produce PVC flooring in China–coal–compared to natural gas-based feedstocks used in the U.S., contribute to the deviation in estimated emissions.

2. Vinyl flooring manufacturers use significant quantities of highly toxic chemicals like PFAS and mercury to produce PVC; these chemicals are hazardous to workers all along the supply chain and endanger frontline and fenceline communities in the U.S. and abroad.

Per- and Polyfluoroalkyl Substances (PFAS), also known as "Forever Chemicals," are widely used in PVC production. Vinyl flooring manufacturers in China, the United States, and in other major manufacturing hubs across the world use PFAS membranes to produce chlorine, which is then used to manufacture PVC. PFAS chemicals, including the ones used in chlorine production - Nafion and polytetrafluoroethylene (PTFE) - are toxic to humans at extremely low levels of exposure, even at concentrations in the parts per trillion range (EPA, 2016). Our report provides the first ever published estimates of the rate of use of PFAS, asbestos, and mercury in PVC flooring production. Our results show that on average, the annual production of PVC flooring at one representative manufacturing plant in Yibin, China used **33 kilograms of PFAS**. The production of Nafion and other PFAS chemicals releases potent greenhouse gases called perfluorocarbons that degrade Earth's ozone layer. Moreover, the environmental fate of Nafion and PTFE membranes used in PVC production around the globe is yet unknown, and very little information exists regarding the disposal of these membranes.

Mercury is also commonly used in PVC manufacturing. In the Yibin plant, mercury is added to catalyze the reaction between chlorine and coal, generating toxic releases of gaseous mercury into the atmosphere and producing climate warming greenhouse gas emissions. Our results show that the Yibin plant uses between 1.1 and 2 kg of mercury per ton of PVC produced. When scaled up to annual PVC production, this amounts to more than **24,000 kg, or approximately 24 metric tons, of mercury** consumed each year.

3. Asbestos is used to produce chlorine to make PVC flooring in the United States – importing asbestos for PVC production represents the last remaining legal use of this toxic mineral fiber.

While asbestos has been largely phased out of use in the U.S. because it is a known carcinogen, the U.S. government still allows the chlor-alkali industry to continue to use asbestos membranes to produce chlorine. PVC manufacturing is the leading consumer of chlorine in the United States and on average, the U.S. imports approximately **373 metric tons of asbestos** from mines in Russia and Brazil each year. Throughout this long, global supply chain–from mining, bagging, shipping, to use in U.S. chemical plants, and finally disposal of membranes in open-air landfills–asbestos can be released into the air and poses a risk of exposure to individuals. As recently as 2021, the U.S. Environmental Protection Agency (EPA) declared that the industrial use of asbestos in chlorine production posed *an unreasonable occupational risk* to workers because of the exposure to asbestos fibers.

In April 2022, EPA announced a draft rule that would prohibit chlor-alkali manufacturers from using asbestos. While this announcement is a positive move toward eliminating the last remaining industrial use of asbestos in the U.S., it is likely that chlor-alkali producers will substitute PFAS-coated membranes for asbestos filters. As described above, PFAS are a class of extremely toxic and environmentally persistent chemicals that endanger human and environmental health.

4. Vinyl flooring production has shifted to China, resulting in increased use of coal and higher carbon dioxide emissions.

Over the past ten years, U.S. vinyl flooring manufacturers shifted the bulk of production from the U.S. to China, where most manufacturers use coal as a feedstock to produce PVC rather than natural gas. In China, chlorine is reacted with coal, using mercury, to produce vinyl chloride monomer (VCM), the building blocks of PVC. This difference from the U.S. process releases enormous quantities of carbon dioxide into the atmosphere. In China, the abundance of cheap, locally mined coal has contributed to its widespread use in PVC flooring production both as an input and as an energy source to fuel manufacturing plants.

In 2020, the U.S. flooring industry sold $23 billion worth of floors, the equivalent of 1.77 billion square meters. The same year, China shipped 406.4 million square meters of vinyl flooring to the U.S., **the equivalent of 20% of all floors sold in the U.S. that year**.[1] U.S. demand for vinyl flooring is driving production in China and contributing to higher emissions of carbon dioxide, per square meter of flooring produced.

[1] STATS: Flooring sales trend slightly lower in 2020. https://www.fcnews.net/2021/05/stats-2020-flooring-sales-industry-stats/

Executive Summary

Increasing awareness of the carbon footprint of materials used in our built environment, as well as concerns about the toxicity of these materials, has highlighted the need for better information regarding the environmental impacts of the products used in our everyday lives. Flooring made of polyvinyl chloride (PVC), marketed as “luxury vinyl tile” (LVT), is increasingly popular amongst purchasers, designers, and homeowners in the United States. However, the name “luxury vinyl tile,” belies the fact that this flooring is a petrochemical product, far from desirable due to its energy-intensive and chemical-dependent production process. This report seeks to address the lack of transparency and accuracy in environmental product declarations (EPDs) for PVC flooring by quantifying the carbon dioxide equivalent (CO_2e) emissions and the consumption of three chemicals of high concern (asbestos, mercury, and PFAS) used within the manufacturing supply chain of PVC flooring. To the best of our knowledge, this report provides the first published estimates of the rate of use of these three toxic chemicals in PVC manufacturing.

In generating this report, Autocase Economic Advisory, alongside Material Research L3C, conducted a cradle-to-site carbon life cycle analysis (LCA) and toxic chemicals analysis using peer-reviewed literature, supplemented with ground truthing, and expert judgment. Two production processes that are representative of the global market for PVC flooring were selected as case studies: the carbide process which is predominantly used to produce PVC in China, and the U.S.-based ethane to ethylene process.

A standard LCA considers the carbon emissions, among other environmental impacts, generated by a material throughout its lifespan–it includes raw material extraction, manufacturing, transportation, installation, use, and disposal. A LCA that considers each of these steps in extraction, production, use, and disposal is also called a cradle-to-grave analysis. This report foregrounds the front end of the PVC flooring life-cycle, using an LCA-based approach to quantify the carbon emissions generated from cradle-to-gate plus transportation-to-site (herein referred to as cradle-to-site). Cradle-to-gate is a boundary condition associated with embodied carbon, carbon footprint, and LCA studies. A study of these boundaries considers all activities starting with the extraction of materials from the earth (the cradle), their transportation, refining, processing and fabrication activities until the material or product is ready to leave the factory gate. Cradle-to-site takes these cradle-to-gate results and adds the transportation of the material or product to its site of use.

While a cradle-to-grave LCA approach is considered the most comprehensive, it was not the focus of this report because of the challenges in understanding the assumptions underlying the use phase and end of life phase of PVC flooring, as reported in manufacturer EPDs. Instead, this report seeks to provide clarity around the cradle-to-site portion of the product life-cycle. In doing so, this report reveals inconsistencies in manufacturer EPDs, bringing to light more accurate estimates of the carbon emissions resulting from carbide-based production in China and ethane to ethylene-based production in the United States.

Flooring industry EPDs calculated using the U.S. supply chain as a baseline, fail to account for a fundamental shift in the political economy of PVC flooring production. Today, PVC flooring made in China is the most common flooring sold in the United States, accounting for over one-quarter of all flooring sold in the U.S.[2] The scale of this trade is enormous. Over the past decade, these shipments to the U.S. increased by 300% and now exceed 5.1 billion square feet per year. If each square foot were connected end-to-end, shipments that arrived in 2020 would run 1,040,000 miles: that's enough vinyl flooring to connect Earth to its Moon, four times over.

Irrespective of its origin, any vinyl flooring sold in the United States has been produced using toxic chemicals, which are released in highly energy intensive processes that also emit climate-warming greenhouse gasses into the atmosphere. This carbon and chemical pollution impacts the entire planet, including people who purchase vinyl flooring far from its place of production.

Vinyl made in China typically uses two particularly toxic substances: mercury, a potent neurotoxin; and, per- and polyfluoroalkyl substances or PFAS, which are associated with many different types of cancer, depressed immune function, and other adverse health effects. In the United States, vinyl flooring is typically made using asbestos, a known human carcinogen. The PVC industry is the last remaining industry legally allowed to import and use hazardous chrysotile asbestos. This asbestos is transported thousands of miles from mines in Brazil and Russia to chlor-alkali plants in the United States. Mine laborers, factory workers, and fenceline communities - whether in China, the United States, Russia, or Brazil - are unnecessarily exposed to toxic chemicals and toxic byproducts because of vinyl flooring production.

Through step-by-step and transparent accounting, this report provides insight into the toxic chemical and carbon equivalent releases generated by vinyl flooring production - these are details that PVC flooring companies do not share with customers and that are not accurately represented in manufacturer EPDs. This report reveals higher levels of carbon dioxide and toxic pollution than flooring corporations have ever declared, whether the PVC is made in the U.S. or China.

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[2] U.S. International Trade Commission Dataweb, HTS Number 3918.1 and 3918.9. https://dataweb.usitc.gov/

Methodology

This LCA-based cradle-to-site analysis estimates the carbon emissions from two market-representative PVC flooring production processes – one originating in the United States and one in China. The first step was to perform a comprehensive analysis and depiction of all the supply chain components to derive the carbon impact across the entire supply chain for PVC flooring. Next, the report conducted a toxic chemicals analysis by estimating the rate of use of PFAS, mercury, and asbestos on a per square meter basis to better understand the environmental health impacts of PVC flooring production.

This LCA-based carbon analysis focused on cradle-to-site elements, which includes raw material extraction and processing (LCA System Boundary Module (A1), transportation of materials to the manufacturer; (A2 and A3), manufacturing of materials into the end product; and (A4) transportation of the product to the installation site, across an average PVC flooring lifespan of 30 years (see Methods for more details on boundaries). The analysis also factors in other materials that make up vinyl flooring, including fillers like limestone, stabilizers, and plasticizers. This analysis assumes that in order to meet consumer expectations in the United States, the flooring made in China contains neither phthalate plasticizers nor lead stabilizers. However, buyer beware: most vinyl flooring made in China still uses phthalates and lead stabilizers.[3]

Results

The results of the cradle-to-site carbon analysis and toxic chemicals used in PVC flooring production are presented in Tables 1 and 2, respectively.

The 30-year cradle-to-site carbon equivalent emissions values per square meter of vinyl tile flooring produced are 34.650 CO_2e kg for the Yibin Plant in China, and 16.319 CO_2e kg for the Occidental Plant in the United States. See Appendix A for estimates of the CO_2e emissions per square meter of vinyl sheet flooring produced.

[3] Du, D, & Stern, N. Analysis of the Chinese PVC Industry. 2021. https://mst.dk/media/220519/analysis-of-the-chinese-pvc-industry.pdf

Table 1. Vinyl tile flooring cradle-to-site carbon analysis for a 30-year period (LCA Boundaries A1-A4; see Methods section for more detail). Values represent the amount of CO_2 equivalent emissions (kg) per square meter of vinyl tile flooring produced. A typical vinyl flooring tile weighs 5.93 kg/m^2.

Source	CO_2 equivalent emissions (kg CO_2/m^2 vinyl tile)	Percent Difference from Manufacturer Reported Value
Vinyl Tile Manufacturer EPD (RFCI)	12.81	**0%**
Occidental Plant, U.S. (ethene-based process)	16.32	**+27%**
Yibin Plant, China (coal-based process)	34.65	**+171%**

Table 2. Estimated rate of toxic chemicals used in vinyl flooring production and yearly consumption of toxics used in vinyl flooring production on a per-plant basis.

Toxic (Production Process)	**Quantity Used** (kg/m^2 of flooring)	**Yearly Consumption Per Plant (kg)**
PFAS (China chlor-alkali)	**0.00000005**	~ **3**
Asbestos (U.S. chlor-alkali)	**0.00003624**	~ **7,788**
Mercury (China VCM)	**0.00020251**	**24,000**

Recommendations

Flooring Manufacturers

1. Embrace transparency by disclosing all product ingredients in EPDs including those that are consumed in the process of PVC manufacturing like mercuric chloride
   a. Detail all assumptions in EPDs about product lifespan, recyclability, use, and maintenance
2. Immediately adopt policies that phase out the use of asbestos, mercury, and PFAS chemicals in PVC production
3. Avoid regrettable substitution and assess any alternative chemicals for safety using GreenScreen for Safer Chemicals or ChemFORWARD databases

Institutional Purchasers and Consumers

1. If possible, keep the flooring you have in place or refinish existing hardwood
2. Consider purchasing healthier flooring like linoleum or ceramic tile instead of PVC flooring
   a. CEH has compiled a purchasing guide that details healthier flooring options and is accessible at the following link: CEH Healthier Flooring Purchasing Guide
   b. In addition, more healthy flooring options can be found at: Greenhealth Approved Flooring
3. Avoid buying other PVC-based products where you can – some examples include vinyl siding for homes, vinyl window treatments, and vinyl blinds.
4. Sign up for our email list to stay up to date on the latest news about CEH's work to protect people from toxic chemicals at CEH.org

Designers

1. Educate your clients about the carbon footprint and toxics concerns associated with PVC flooring.
2. Reject the latest trend toward luxury vinyl tile.
3. Wherever possible, recommend flooring with the lowest carbon *and* toxics footprint, to your clients.
4. For more information on healthier flooring options visit:
   a. CEH Healthier Flooring Purchasing Guide
   b. Greenhealth Approved Flooring

Scope of Report

The supply chain for PVC production is opaque and difficult to trace. This report sought to capture the full production process, to the best of our knowledge, using expert judgment, and peer-reviewed academic literature. Still, there are some notable omissions in estimated carbon dioxide equivalents from parts of the supply chain and production process due to a lack of peer-reviewed information. These omissions are highlighted in Appendix A, Figures A1 and A2.

Consistent with standard LCA practice, carbon emissions for materials within PVC flooring that are under 1% of the whole material composition were excluded.[4] Also, this analysis does not quantify the carbon equivalent releases from toxics/chemicals used in the use phase of the flooring (i.e., cleaning materials, detergents). It only captures the carbon emissions of three toxic chemicals (asbestos, mercury, PFAS) that are used to produce PVC flooring, although there are other known toxic chemicals used in the manufacturing of PVC.

The two manufacturing sites examined in this report were selected because their production sizes are close to the median, and their technologies are representative of what is used in their home countries.

[4] Quantis. Guidelines for environmental life cycle assessment. 2011. http://www.eeq.ca/wp-content/uploads/lignesdirectrices_emballages_engl.pdf

1. Introduction

The existential threats posed by climate change have shaped United States national and international policy (The United States Government, 2021a, 2021b) and caused governments around the world to commit to ambitious greenhouse gas reduction targets in the hopes of avoiding catastrophic impacts to Earth's life supporting systems (European Commission, n.d.; Government of Canada, 2020). As part of climate mitigation efforts, there is growing interest within governments, corporations, real estate owners, and building occupants (workers, renters, etc.) around the topic of decarbonization in the built environment. While operational carbon has been an important consideration in the built environment (offices, schools, cities, etc.), embodied carbon in materials selection is now recognized as a key driver in achieving global decarbonization goals (World Green Building Council, 2019; Pembina Institute, 2020).

As low-hanging fruit for decarbonization is already underway for power utilities and building operations (e.g., solar energy, building energy efficiency), corporations and institutions are turning to the global supply chain to tackle emissions from material extraction, manufacturing, transportation, and more (Spiller, 2021). Furthermore, consumer and occupant demand for healthy spaces – free of volatile organic compounds (VOCs) and toxics – has never been more pronounced (Wang, 2007; Scott, 2017; Vallette, 2017). With organizations striving to reduce their carbon emissions and improve their employees' and occupants' health, acute awareness of materials selection is now a fundamental part of building design.

Flooring is a necessary and high-volume product in the built environment. With the increase in globalization, builders, designers, and retailers have gravitated towards cheaper flooring made from polyvinyl chloride (PVC) over other, more expensive alternatives. While this provides a low-cost product option, it entails significant hidden costs for the environment and the health of workers, frontline and fenceline communities around the globe. In recent years, PVC flooring has been rebranded as Luxary vinyl tile or LVT. LVT is being promoted by home makeover influencers, home improvement mega-stores, architects, designers, and more. Yet, while this flooring may be called "luxury", it is still just plastic flooring, manufactured with toxic chemicals long known to cause harm to people and the planet.

Petrochemical-based plastics are increasingly recognized as significant contributors to the climate crisis and global pollution crisis. In the United States, the industry's total emissions of greenhouse gasses are expected to surpass those of coal-fired power plants within this decade (Beyond Plastics 2021). Plastic industry pollution comes not only from the production of the plastics themselves, but also from the extraction of fossil fuels and toxic chemicals that are used as inputs in production. The dominant type of plastic building material is PVC. An estimated 70% of all PVC is consumed by building and construction worldwide (Geyer et al. 2017). The PVC industry dominates high volume products like pipes and roofing membranes, and interior finishes, especially flooring and wallpaper. PVC flooring produces more externalities than many flooring alternatives, due its profound reliance on fossil fuels for its core components during production, and reliance on toxic chemicals across various stages of manufacturing. Another important megatrend is the growing size of buildings in the United States. Between 1973 and 2015, the average house size nearly doubled, from 551 to 1,058 square feet per person (51 to 98 square meters). The production of PVC to meet this demand supports some of the most toxic industries on earth, including mercury and asbestos mining.

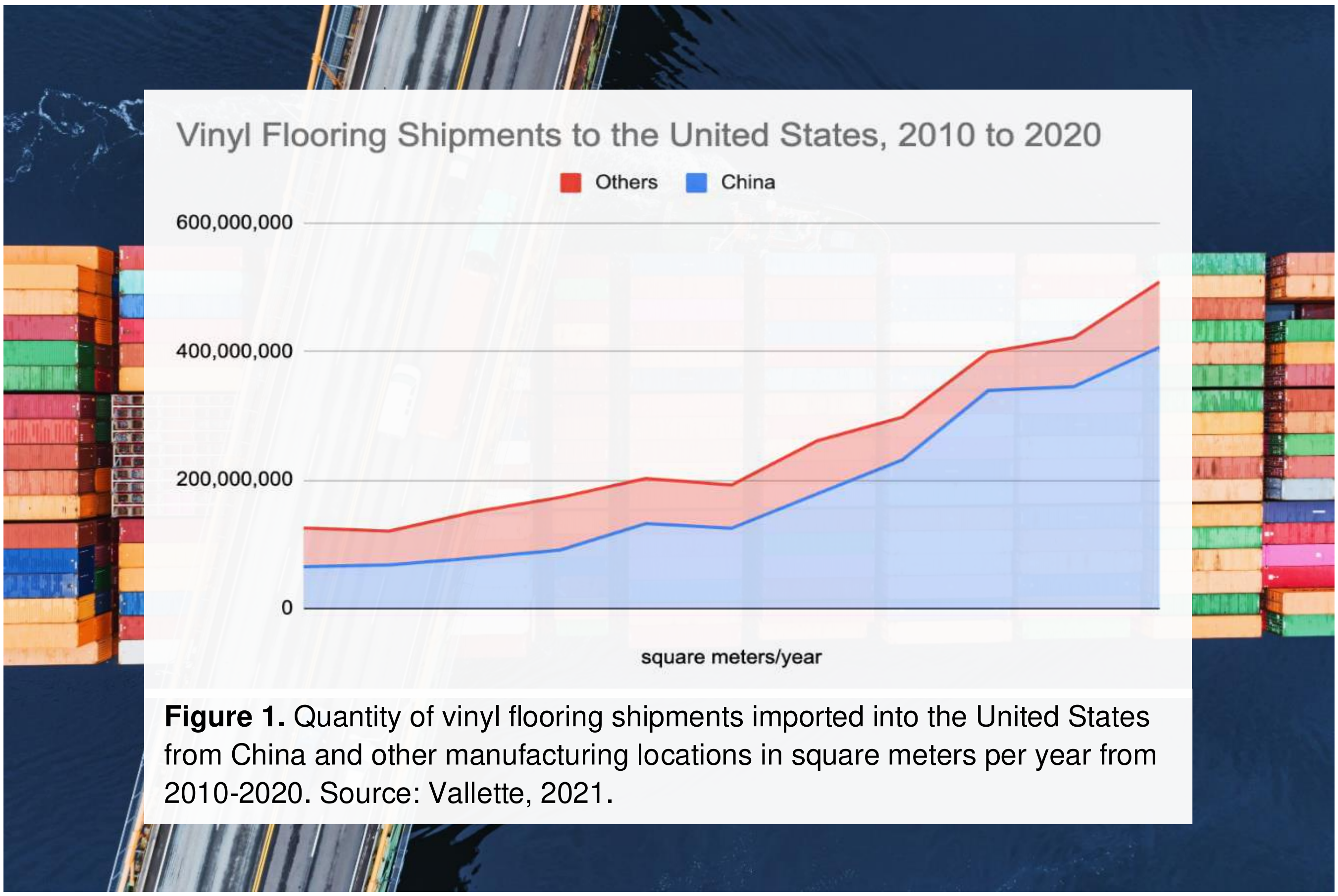

Figure 1. Quantity of vinyl flooring shipments imported into the United States from China and other manufacturing locations in square meters per year from 2010-2020. Source: Vallette, 2021.

In addition to mining, there are two remarkably polluting stages of PVC production.

1. **Chlorine Production**
   The first is chlorine production, commonly referred to as chlor-alkali production, an energy intensive process that splits brine into chlorine and caustic soda. About half of the chlor-alkali plants in the United States use asbestos-coated diaphragms.[5] The U.S. is an outlier in the continued use of asbestos for PVC production. In China and much of the rest of the world, brine is processed using membranes coated in man-made per- and polyfluoroalkyl (PFAS) chemicals, which, like asbestos, are highly toxic and known to cause a wide range of adverse human health effects.

2. **Vinyl Chloride Production**
   The second stage in PVC production reacts chlorine with a carbon source to produce vinyl chloride monomer, the building blocks of PVC. In the U.S., chlorine is reacted with ethylene, a natural gas obtained from hydraulic fracturing or fracking. The process of reacting chlorine with ethylene creates and releases potent climate warming and health harming toxics like ethylene dichloride gas. In much of China, chlorine is reacted with a different fossil fuel–coal–using mercury catalysts and emitting mercuric chloride and ozone-depleting organochlorine compounds into the atmosphere.

China's production process has proven to be cheaper than that in the U.S., and much of the flooring industry has abandoned the U.S. in favor of China's PVC factories. As discussed below, at least one-quarter of all floors sold in the U.S. today are vinyl floors made in China. Since 2012, at least 18 flooring factories have closed in the United States, according to news reports.[6] More than 2,500 workers have lost their jobs in the closures, as imports of PVC flooring from China soared, from 78.5 million square meters in 2012 to 406 million square meters in 2020 (ITC Dataweb).

In addition to the pollution released during production, PVC floors pose waste management challenges. Most commercial PVC flooring companies provide only 5- or 10-year warranties for their products. There is little to no recycling of PVC floors due to their complex construction and presence of chemical biocides, stabilizers, plasticizers and topcoats. Most PVC flooring companies have policies against using post-consumer recycled PVC due to contamination

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[5] Vallette et al., 2018. Chlorine and Building Materials: A Global Inventory of Production Technologies, Market, and Pollution Phase 1: Africa, The Americas, and Europe.
https://www.researchgate.net/publication/326631987_Chlorine_and_Building_Materials_A_Global_Inventory_of_Production_Technologies_Markets_and_Pollution_Phase_1_Africa_The_Americas_and_Europe

[6] Center for Environmental Health, Material Research L3C, & Autocase. Webinar. 2021.
https://www.youtube.com/watch?v=Q2MzExpTFbY&t=1033s

concerns (Vallette, 2015), including from the use of phthalate plasticizers and lead stabilizers, which continue to be common in China (China-Direct Biz, 2021).

Industry marketing materials in the United States do not reflect these realities. The flooring industry creates illusions of transparency through opaque declarations that aggregate old industry data into incomplete and unverifiable estimates. The industry's Environmental Product Declarations, for instance, do not mention asbestos, mercury or PFAS, nor do they provide an itemized accounting for their claims about carbon dioxide emissions. In addition, some manufacturers even claim their PVC products are "carbon neutral" due to corporate carbon off-sets. The purpose of this report is to bring such details to light. This step-by-step and transparent inventory of inputs and releases establishes a clear-eyed view of the toxic substances and greenhouse gas-intensive processes upon which this industry relies.

To address these challenges, change industry dynamics, and help organizations minimize their carbon footprint, the Center for Environmental Health (CEH) was interested in a set of comparative analytics that allow for more informed, data-backed decisions in the selection of flooring materials within the built environment. As such, CEH engaged Autocase Economic Advisory (AEA), in collaboration with Material Research L3C (herein referred to as "Material Research"), to conduct a custom, in-depth life cycle analysis (LCA)-based quantification of carbon dioxide equivalent emissions and toxic chemical inputs in PVC production using existing data and supplemented with ground truthing and expert judgment. The carbon dioxide equivalent emissions (herein referred to as "carbon" or "CO_2e") calculation within this LCA-based approach include a cradle-to-site analysis of production systems and provides a comprehensive evaluation of material extraction, transportation, and manufacturing processes for PVC flooring. This LCA-based carbon analysis is supplemented with a quantification of toxic chemicals (specifically, asbestos, mercury, and PFAS) used within PVC production processes.

An extensive investigation of two specific supply chains of PVC flooring was completed in this analysis- one from Yibin Haifeng Herui Co. in Yibin, Sichuan, China (herein referred to as "Yibin" or "the Yibin plant") and the other from Occidental Petroleum in Ingleside, Texas, U.S. (herein referred to as "Occidental" or "the Occidental plant"). Each plant has a specific transportation network and supply chain and based on available trade data, both are assumed to deliver to the east coast of the United States (Descartes, n.d.). These two plants were selected as representatives of the industry because they supply the U.S. market, their production sizes are close to the median, and their technologies are representative of what is used in their home countries (Vallette et al., 2018).

Concerns about current EPDs for PVC flooring:

1) The EPD certification body, NSF, relies on limited and outdated data. NSF has product category rules for flooring EPDs which are derived from Franklin and Associates' "LCA

of 9 plastic resins" (Franklin Associates, 2011). Franklin's LCA for PVC is based on data provided by one company in the U.S. in 2003 and is the standard dataset upon which all other analyses have followed. It is impossible to tell from this LCA for PVC flooring what stages and inputs of the critical raw material extraction phase are being considered. Furthermore, this LCA does not provide an accounting of CO_2e releases for specific stages of production, and thus it is not possible to critically understand the quality of the foundational data behind the flooring industry's declarations.

2) These incomplete LCAs, based on outdated U.S. data, serve as the foundation for EPDs for products manufactured in both the U.S. and China, despite the fact that China uses coal rather than natural gas as a feedstock for PVC production.
3) The Resilient Floor Covering Institute represents the industry in the United States, and, in 2019, it issued an EPD that is assigned to most vinyl tile flooring sold in the U.S. today. The EPD states that "product accounted for in this EPD represents around 90% of heterogeneous vinyl flooring sold in North America." However, trade and other market data reveal that most of this kind of flooring sold in the U.S. originates in China, where manufacturing conditions are quite different than those assumed in the EPD based on US data. Moreover, the EPD uses a mixture of data from Europe, the U.S. and China in its calculations, making it difficult to disentangle and interpret the underlying numbers.
4) Furthermore, typical LCAs tend to omit overseas emissions of the delivery of the product to foreign markets which can account for substantial carbon emissions.

Instead of relying on manufacturer EPDs or LCAs to estimate the carbon dioxide emissions from PVC production, this report compiles and evaluates information about inputs and outputs throughout the extensive PVC production process in China and the U.S to come to a more accurate accounting of the carbon emissions generated from PVC flooring from cradle-to-site. This analysis estimates the amount of CO_2e released at each stage of PVC production, using academically verified sources and expert judgment. Autocase identified 26 distinct stages of extraction, production, and delivery of vinyl floors from China to the U.S. market, and 23 stages in the U.S.-based cradle-to-site supply chain.

This report makes some assumptions regarding the carbon emissions from PVC production processes. There are also some aspects of the PVC lifecycle that were excluded from this report due to a lack of academically-verified data - these include, but are not limited to:

- This analysis does not include carbon emissions associated with material components of PVC flooring that are under 1% of the whole material composition.
- This analysis does not include the carbon emissions associated with the maintenance and use of the flooring (i.e., cleaning materials, detergents).
- Carbon emissions from the installation, use, and end-of-life phase of PVC flooring are valued using the manufacturer's EPD carbon emission estimates (NOX Corporation, 2018).

- It is likely that in a commercial or industrial setting that flooring is replaced more often than the 30 years that manufacturer EPDs cite.

2. Methodology

2.1 Product Definition and Information

PVC flooring is standardized to two forms:

1) Sheet flooring, defined as a heterogeneous sheet of 1 square meter (m^2). A heterogeneous (standard) PVC floor is considered to be a multi-layer flooring, consisting of a wear layer and a backing (as opposed to homogeneous vinyl sheet flooring which does not carry a backing) (Pharos, 2016). Flooring composition and weight values are taken from NOX Corporation's EPD for "luxury sheet vinyl" (NOX Corporation, 2018) and a total weight of 3.55 kilograms (kg)/m^2.
2) Vinyl tile flooring is defined by the industry's Resilient Floor Covering Institute (RFCI) as a single or multiple layer product primarily made from limestone, PVC, plasticizers and additives (Table 3). Flooring composition and weight values are taken from the Resilient Floor Covering Institute's EPD for LVT sold in North America (Resilient Floor Covering Institute, 2019), with a total weight of 5.93 kg/m^2.

2.2 Material Composition

To complete a comprehensive analysis, we included all available data, within the limits of available academic, peer-reviewed research that matches with identifiable components of industry EPDs for vinyl sheet and tile flooring.

Sheet vinyl floors typically weigh around 3.55 kilograms (7.83 pounds) per square meter; 45% of this weight (1.6 kilograms) is PVC (Nox Corporation, 2018). Tile vinyl floors, which the industry typically calls "Luxary vinyl tile," typically weigh 5.9 kilograms (13.07 pounds) and 33% of this is PVC (1.9 kilograms per square meter). (RFCI, 2019) This means floors shipped from China to the U.S. in 2020 contained between 650 million and 770 million kilograms of PVC.

In the case of vinyl sheet flooring, identifiable components include PVC, filler, and plasticizer, which account for 95.5% of the product as a whole. This EPD states that the 4.6% balance includes stabilizers, pigments, coatings and "other." The precise percentages and/or identities for these individual materials are not disclosed, which prevents direct comparisons. Therefore, this LCA's boundaries for sheet vinyl flooring include only PVC, filler, and plasticizer.

The Resilient Floor Covering Institute's EPD for tile (LVT) flooring states the composition as 53% fillers, 33% resin, 9.0% plasticizer, 0.2% pigment, and 5.3% additives and "other" unquantifiable components. This LCA's boundaries for LVT flooring include only limestone, PVC filler, plasticizer and stabilizer, which represent 94.7% of the product as a whole. (The filler and resin percentages provided in the EPD appear to have been rounded up as the total is 100.5%. For this report's calculations, 0.25% weight shares are deducted from the filler and resin values.) In addition, this analysis excludes the 0.2% pigment as it is below the 1% cutoff that is standard LCA practice.

Therefore, our analysis does not include 3.35% of the composition of sheet vinyl flooring. It does not include 5.5% of the composition of tile flooring (Table 3). Among the uncounted components are the floors' topcoat layers. The industry does not typically disclose the precise composition of the topcoat layer in sheet vinyl or LVT flooring. No LCAs or EPDs could be found to determine the carbon emission impact of this polymer that is described generally as "urethane acrylic" and includes numerous undisclosed additives.

No recycled material was included in the analysis because none were declared by the manufacturer or distributor (NOX Corporation, 2018; Resilient Floor Covering Institute, 2019). Due to contamination concerns, major purchasers and flooring manufacturers, including Tarkett, Interface, Mohawk, and Armstrong have policies against using any post-consumer scrap in imported resilient flooring (Vallette, 2015).

Table 3. Material composition of vinyl tile flooring as reported in RFCI environmental product declaration for “luxury vinyl tile” flooring.

Material Name	Function	% Weight (Whole, Non-Recycled)[7]	Weight per square meter (kg)	Included in Analysis
Limestone	Fillers	52.75%	3.14	Yes
Polyvinyl chloride (PVC)	Resin	32.75%	1.96	Yes
Bis(2-ethylhexyl) terephthalate*	Plasticizer	9.0%	0.54	Yes
Not named	Pigment	0.2%	0.01	No
Not named	Additives	0.8%	0.47	No
Not named	Other	4.5%	0.27	No
Total Product			**5.93**	

(*) This material is not named in the NOX or RFCI EPD for this function. However, it is the industry standard for PVC flooring sold in the United States, according to the Pharos Project’s common product records for heterogeneous vinyl resilient sheet flooring and luxury vinyl tile. Note: Percentages for PVC and limestone in sheet and tile, and plasticizer in tile, were adjusted to match EPD rounding (plus 0.1% for sheet components, minute 0.25% for tile components).

[7] Values may not add up to totals due to rounding.

2.3 Supply Chain Overview

Two specific geographic supply chains, with different PVC production processes, are included in this analysis. Each plant has a specific transportation network and supply chain, and both are assumed to deliver to the east coast of the U.S. based on available trade data (Descartes, n.d.). These supply chains are representative of typical conditions in their respective countries.

PVC floors made in the U.S. begin through the ethane to ethylene production process at Occidental Chemical, a vinyl chloride monomer (VCM) plant in Ingleside/Gregory, Texas, U.S. At this location brine and ethane are processed and turned into VCM. The brine splitting is accomplished with an asbestos diaphragm membrane. The Occidental plant in Ingleside is powered through a dedicated natural gas plant. This VCM is shipped to Cartagena, Colombia, where it is polymerized into PVC. The PVC is then shipped to Pedricktown, New Jersey, and then driven to Armstrongs' plant in Lancaster, Pennsylvania, where it is combined with several other compounds and materials to create PVC flooring. This is then delivered to customers around the U.S.

PVC floors made in China begin through the carbide production process at Yibin, a PVC plant in Yibin, China. This plant is fully integrated, from the brine splitting with a Nafion-coated, polytetrafluoroethylene (PTFE) membrane, to the creation of acetylene from coal, the creation of VCM and polymerization into PVC, and the final flooring assembly. This plant is powered by a dedicated coal fired plant. The finished product is shipped by rail to the port of Shanghai, where it travels by cargo ship to Norfolk, Virginia. The finished product is then delivered to customers around the U.S.

Within the past decade, U.S. plastic flooring manufacturers shifted the bulk of their production from the U.S. to China. Imports of PVC floor and wall coverings from China rose six-fold between 2011 and 2020, from 64.8 million square meters in 2011 to 406.4 million square meters in 2020 (see chart).[8]

The Yibin plant that is a focus of our analysis is a major supplier to the U.S. market. In 2020 alone, Armstrong imported 3,270 metric tons of PVC floors from Yibin Tianye New Material, according to records in the global trade database (Descartes, n.d.). This is the equivalent to 551,000 square meters of LVT or 921,000 square meters of sheet vinyl flooring.

[8] U.S. International Trade Commission Dataweb, HTS Number 3918.1. https://dataweb.usitc.gov/

In 2020, total flooring sales in the U.S. were around 1.85 billion square meters.[9] Most PVC flooring sold in the U.S. now is imported, and 80% is from China. As discussed above, over 400 million square meters of plastic resilient floors arrived in the U.S. from China that year and accounted for more than 20 percent of all floors sold in the U.S (U.S. International Trade Commission Dataweb).

In addition to these resilient floors, the U.S. imported 380 million square meters of plastic carpeting, which are usually comprised of plastic fibers on a PVC backing. (Floor Covering News) This represents another 20.5% of the flooring sold in the U.S. in 2020. Therefore, more than 40% of all flooring sold in the U.S. is either resilient flooring or carpet containing PVC from China.

2.4 LCA System Boundaries

The LCA-based carbon analysis is focused on cradle-to-site elements, which includes raw material extraction and processing (LCA System Boundary Module A1), transportation of materials to the manufacturer (A2), manufacturing of materials into final end product (A3), and transportation of the product to the installation site (A4). Sections 2.1.4.1 to 2.1.4.4. describe all studies used in the carbon LCA estimates for each LCA System Boundary Code. All values from studies used to derive final results are included in Appendix B.

This report focuses on the front end of the life-cycle, using an LCA-based approach to quantify the carbon emissions generated from cradle-to-gate plus transportation-to-site - called cradle-to-site. While a cradle-to-grave LCA approach is considered the most comprehensive, it was not the focus of this report because of the challenges in understanding the assumptions underlying the use phase and end of life phase of products, as reported in manufacturer EPDs. Instead, this report seeks to provide clarity around the cradle-to-site portion of the product life cycle. In doing so, this report reveals inconsistencies in manufacturer EPDs, brings to light more accurate estimates of the carbon emissions resulting from carbide-based production that occurs in China and the United States ethane-to-ethylene process.

[9] According to two trade journals, between 19 and 23 billion square feet of floor coverings were sold in 2020, which is the equivalent of 1,765,157,760 to 2,136,769,920 square meters. . Floor Covering Weekly, Statistical Report 2020. July 26, 2021.
https://cdn.coverstand.com/26543/716283/3fa0d3392bcccfad62714b6d81856c382df26fe7.1.pdf and Floor Coverning News. STATS: Flooring sales trend slightly lower in 2020.
https://www.fcnews.net/2021/05/stats-2020-flooring-sales-industry-stats/ In 2020, according to US ITC Databab statistics, China shipped 4.

Raw Material Extraction and Processing (A1)

The creation of PVC flooring in this report is calculated for two distinct production processes, the carbide process used in China and the ethane to ethylene process used in the U.S. The commonality between these processes comes from the splitting of brine. Hong et al. (2014) detail how the brine splitting process can be analyzed on a life cycle basis from multiple angles, considering that there are multiple methodologies to create brine. In Hong et al. (2014), the process was centered around the production of chlorine and caustic soda in Shandong Province, China. A deep bore well is drilled into brine rich underground sources, and brine is extracted along an assumed 30 km pipe. It is then transported 100 km by truck to the brine splitting site, where electricity forms the greatest share of emissions. The electricity grid in China is assumed to be a national standard of mainly coal, with only 17.1% hydroelectric (Hong et al., 2014). To convert the total emissions of this process to the U.S. production process, the electricity emissions were re-calculated assuming that all energy at the Occidental plant where the brine splitting occurs is provided by the natural gas plant. Transportation distances, and the location of the brine extraction, are assumed to be the same in both countries for the important reason that the location of the brine in relation to the Yibin and Occidental plants is in the nearby vicinity in both scenarios.

Where the carbide and the ethane to ethylene process differ is in the origin of the other important element within PVC production, VCM (Franke et al, 2014). In the carbide process, coal is mined and transported by rail to the Yibin plant, where it is transformed through several highly polluting steps into acetylene. This pollution involves carbon emissions from the extraction & transportation of coal, the coking of coal, carbide production, and acetylene preparation (Franke et al, 2014) and represents the CO_2e emissions from primary energy and the supply chain (feedstock). Acetylene is reacted with chlorine, in the presence of mercury as a catalyst, to create VCM (Franke et al, 2014), which is then polymerized into PVC (Gaines and Shen, 1980). The Yibin plant has the capacity to produce 500,000 tons of VCM per year. This is powered by a coal plant, with emissions from the plant (GREET, 2020) representing the emissions from the burning of the coal to generate electricity (secondary energy/fuel) (Franke et al, 2014).

From inputs of brine and ethane, the Occidental plant creates its own primary chemicals: chlorine, from the chlor-alkali plant, and ethylene, from the ethylene plant. Chlorine is reacted with ethylene and oxygen, making ethylene dichloride (EDC). Another cracker onsite cracks EDC to make VCM (HBN, 2018). From this, the Occidental plant has the capacity to produce 1 million metric tons of VCM per year (ICIS, 2018). VCM production at Occidental generates carbon emissions through three pathways:

1. Direct CO_2e emissions (in 2019) for the Occidental plant, sourced from the U.S. EPA's Facility Level Information on GreenHouse gasses Tool (FLIGHT, 2019).
2. Releases of natural gas, in extraction and distribution and processing (Howarth & Jacobson, 2021), before reaching Occidental's power plant, Ingleside Cogeneration (EIA, 2019).
3. Cracker production capacity requires the delivery of ethane, which results in methane releases at the wellhead (Howarth & Jacobson, 2021; National Center for Biotechnology Information, 2021a & 2021b).

The methane emission estimates from 2 and 3 follow EPA's standard 100-year (GWP 100) comparison of methane to carbon dioxide (EPA, 2021). The completed VCM is then transported to Cartagena, Colombia, where it is polymerized into PVC (Gaines and Shen, 1980), with energy use emissions calculated using the Colombia power grid (IEA, 2019; GREET, 2020).

Limitations with underlying data availability and conversion information prevented the team from including the mining/extraction related carbon emissions for coal and mercury.

Transportation of Raw Materials to Manufacturing (A2) and Transportation of Manufactured Product to Site (A4)

Transportation is a key component of the analysis, with different types of intermodal movement of raw materials and finished products across both production processes.

Carbon impacts from transportation of the PVC in the U.S. production process begins with the VCM production at the Occidental plant. The completed VCM is shipped by boat to Cartagena (3,033 kilometers [km]), Colombia, where it is polymerized at the Mexichem plant. The finished PVC is then sent to Pedricktown, New Jersey (3,353 km), where it is driven by truck to Lancaster, Pennsylvania (103 km), to be made into PVC flooring at Armstrong's floor plant. Finished floors are distributed an average 800 km distance from the plant.

As all stages of the manufacturing of PVC flooring are completed at the Yibin plant, carbon impacts from transportation occur with the moving of PVC flooring to Shanghai. This is accomplished by trucking the flooring to the railyard at Yibin (68.5 km), then transporting it by rail to Shanghai (1,974 km). From there the product is shipped by large cargo vessel to Norfolk, Virginia (19,244 km) and then distributed on an average 800 km distance from the port.

Transportation emissions for trucks and freight rail are sourced from GREET (2020). These are wheel to well emissions, including all carbon emitted for fuel in extraction, refining, distribution, and use in vehicles. Shipping vessel emissions come from the Clean Cargo Working Group (CCWG), a BSR led initiative (CCWG, 2014). Emissions for different trade routes are attributed per TEU (twenty-foot equivalent unit) kilometer, and attributed based on the volume of the PVC flooring in each TEU.

Manufacturing of Product (A3)

The manufacturing process involves combining PVC with various materials, under heat and pressure in multiple layers. Several coatings of material are applied in this energy intensive process (Freedman, 2005).

These materials include a filler of limestone, which is detailed from the extraction of rock from mines with a quarrying process in Thailand, to crushing of the rock into powder and transportation to a manufacturing site (Kittipongvises, 2017). Limestone is assumed to be quarried with similar heavy machinery and process, from locations in the region of the Yibin and Occidental plants.

A plasticizer is used to increase the malleability of PVC. The current industry standard plasticizer for floors sold in the U.S. market is bis(2-ethylhexyl) terephthalate. This plasticizer's carbon impact is analyzed by Li (2013) with the use of the U.S. EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI). Note: The NOX sheet flooring EPD that provides the compositional proportions used in our analysis lists an orthophthalate, di-isoheptyl phthalate, that is heretofore unknown in the U.S. market. Many flooring distributors have policies against the use of orthophthalates in the United States.

Carbon emissions from energy use in the manufacturing process in the U.S. are applied for the Lancaster, Pennsylvania eGRID region (eGRID, 2019), while for the manufacturing process in China, emissions are attributed from a coal fired power plant (GREET, 2020).

3. PVC Flooring Carbon Analysis Results

The results show that the Yibin (carbide) production process in China results in higher carbon emissions from cradle-to-site, than the Occidental (ethane to ethylene) production process in the U.S. This is due to the more carbon pollutant heavy process of carbide production (coal) and the farther distance the PVC flooring has to be transported to reach the product site (Table 4). The current carbon emission estimate from manufacturer EPDs show a lower carbon impact than the production processes reviewed in this report (Table 4). The difference is due mainly to the production stage (A1-A3), where the analyzed PVC production processes are more carbon intensive than that estimated by the EPDs. An LCA-based cradle-to-site carbon quantification, that details all the calculations and conversions used to arrive at these estimated CO2e values is provided in Appendix B.

The benefit of this carbon quantification comparison, relative to the carbon emission estimates from the EPDs, is threefold:

1. The detailed delineation of the production stage into its components, allowing readers to understand what is involved within each step of the production process and the quantification of carbon emissions from each stage.
2. Transparent accounting of the methodology used to arrive at the final values, allowing readers to understand how we derived the final results.
3. The clear breakdown structure of the supply chain for both production processes, allowing readers insight into how PVC flooring is created.

Table 4. PVC Flooring Cradle-to-Site Carbon Analysis by LCA System Boundary (30 Years)

Code	LCA System Boundary Description	Yibin, China	Occidental, U.S.	PVC Flooring EPD (RFCI)	Units
A1 - A3	Raw Material Supply, Transportation of Raw Materials, & Manufacturing	34.19	16.12	11.90	CO_2e kg (cradle-to-site)
A4	Transportation to Site	0.46	0.20	0.91	
Total		**34.65**	**16.32**	**12.81**	

3.1 PVC Flooring Toxic Chemicals Results

Highly toxic chemicals are used throughout the manufacturing of PVC flooring; from the extraction of raw materials to disposal of flooring, toxic chemicals are necessary inputs and dangerous byproducts of PVC production. These chemicals pose a threat to the health of workers, fenceline communities, and the environment. In the following section, we provide the first estimates of the amount of mercury, asbestos, and PFAS used in PVC flooring production. Other hazardous chemicals associated with PVC production, including vinyl chloride monomer, a known human carcinogen (IRIS, n.d.), and ethylene dichloride (EPA, 2000), a probable human carcinogen, were not quantified although the health effects caused by exposure to these chemicals is discussed below.

The amount of toxic chemicals utilized in both PVC production processes, per square meter of PVC flooring, are listed in Table 5. The asbestos value only applies to the brine- to-chlorine chlor-alkali process in the representative U.S. plant, whereas mercury and PFAS occur only in the chlor-alkali and carbide production process in the representative plant in China.

Table 5. Toxics Chemicals Utilized in PVC Flooring Production in Representative Plants

Toxic (Production Process)	Yearly Consumption per Plant (kg)
Asbestos (U.S., chlor-alkali)	**7,788**
PFAS (China, chlor-alkali)	**3**
Mercury (China, VCM)	**>24,000**

Using plant level VCM production capacity data from Occidental and Yibin, the amount of toxic chemicals used in each production process can be scaled up (converting VCM to PVC using Gaines and Shen (1980)) to the plant level. The Occidental plant in Ingleside, Texas, has a reported capacity to produce 1,090,000 metric tons VCM per year.[10] The Yibin plant has the capacity to produce 500,000 metric tons of PVC (CCM 2014), which requires the production of 515,000 metric tons of VCM, based on 1.03:1 conversion ratio (HBN 2018). This results in estimates of 7,788 kg of asbestos used by the Occidental plant and at least 24,000 kg of mercury and 3 kg of PFAS by the Yibin plant for the production of PVC (Table 13).

[10] Bowen, B. Chemical Profile: US VCM. 2018 https://www.icis.com/subscriber/icb/chemicalprofile?commodityId=10197&regionId=10011

3.2 Occupational and Environmental Health Risks of Toxic Chemicals Used in PVC production

Asbestos

Asbestos is the name of a group of naturally occurring mineral fibers once widely used in many industrial applications. There are six distinct fiber types of asbestos, each made up of a different mineral. Chrysotile asbestos is the only type still imported and in use in the United States - it is the primary component of diaphragm filters used in chlor-alkali production in the United States (EPA 2020). The asbestos diaphragm acts as a filter to separate brine into chlorine and sodium hydroxide in water. All asbestos imports into the United States are destined to chlor-alkali production, which is also the last remaining legal use of asbestos in the country (EPA 2020).

The Ingleside plant consumes at least 16.5 metric tons of asbestos per year in the production of chlorine.[11] The Ingleside plant's primary purpose is to produce VCM, for which it has an annual capacity of 1,090,000 tons.[12] Therefore, it consumes at least one ton of asbestos for every 66,000 tons of VCM production.

In 2020, Occidental Chemical in Ingleside imported 8.4 metric tons of asbestos from Ural Chrysotile of Yekaterinburg, Russia. More commonly, Occidental and other U.S. consumers import asbestos from a mine in Brazil. From the mining of chrysotile minerals in Brazil and Russia, to the transport to the United States, processing of asbestos diaphragms, and the use and disposal of these diaphragms, there are numerous opportunities for occupational exposure to asbestos (*ibid)*.

Over the years, research has shown a strong association between asbestos inhalation and lung damage in the form of asbestosis and the development of cancers including pleural mesothelioma and lung cancer (ATSDR, n.d.; Cugell & Kamp, 2004). Mesothelioma is a rare form of cancer associated with asbestos exposure that has a high incidence of mortality (EPA 2020). The well documented health effects from asbestos exposure have prompted a ban on asbestos in the majority of industrial processes across the U.S. In chlor-alkali production, workers handle asbestos while

[11] 16.5 metric tons is based upon the median weight of asbestos imported by Occidental in the U.S. (52.48 metric tons/year between 2015 and 2021, per Datamyne records), and the proportion of its Ingleside plant's chlorine production capacity to its overall asbestos-based capacity in the country (23.9%). This is likely a low estimate. This plant's expected proportion of asbestos imports, based on its relative capacity to overall production in the U.S., is 29.5 tons out of an median value of 300 metric tons per year between 2016 and 2020 (based on USGS 2021 import data and HBN 2019 capacity data).

[12] https://www.icis.com/subscriber/icb/chemicalprofile?commodityId=10197&regionId=10011

adding the fibers into diaphragm filters and during disposal of used diaphragms (Crook and Mousavi 2016). Throughout these processes, small asbestos fibers can be emitted to the air and settle onto surfaces where they can later be resuspended. Asbestos fibers suspended in the air can spread throughout the workplace environment, posing an occupational health risk even to those workers that do not directly handle asbestos diaphragms (EPA 2020). While asbestos is not present in PVC flooring, its use in chlor-alkali production - a critical intermediary step in the production of flooring - threatens the health and safety of workers.

Asbestos is released from chlor-alkali plants into the air, water, and municipal waste landfills. Between 2012 and 2016, Occidental Ingleside reported releasing an average of 7.32 kilograms of asbestos per year into the air. (HBN 2018).

In 2020, the United States EPA released a risk evaluation for chrysotile asbestos and deemed that the processing and industrial use of asbestos diaphragms in chlor-alkali production posed an unreasonable risk to workers (EPA 2020, p. 32). In their risk evaluation, EPA concluded that workers are at an elevated risk of developing lung cancer and mesothelioma because of inhalation of carcinogenic chrysotile fibers.

In April 2022, EPA announced a draft rule that would prohibit chlor-alkali manufacturers from using asbestos. While this announcement is a positive move towards eliminating the last remaining industrial use of asbestos in the U.S., it is likely that chlor-alkali producers will substitute PFAS-coated membranes for asbestos filters. As described in greater detail below, PFAS are a class of extremely toxic and environmentally persistent chemicals that endanger human and environmental health. The regrettable substitution of PFAS for asbestos should be explicitly banned in EPA's rulemaking.

The amount of asbestos used within PVC flooring manufacturing is measured on a per m^2 of floor basis through the use of publicly available trade data (USGS, 2020; Descartes, n.d.). As the chlor-alkali process is the last legal use of asbestos in the U.S., recent year imports for each company and each plant give a clear indication to this mineral's rate of use in manufacturing, when adjusting for stockpiling of the product.

To assess asbestos carbon emissions across the U.S. production process, we use the CML2001 Methodology from Mori et al. (2021) to capture the extraction of asbestos. The U.S. imports their asbestos from Brazil (USGS, 2020; Descartes, n.d.). Asbestos is transported via truck (1,500 km) from the mine to the Port at Salvador, Brazil. The product is then shipped by ocean freight to Ingleside, Texas (8675 km). Brazil banned the domestic use of asbestos in 2017 but continues to allow mining for exports.

PFAS

In most of the world outside of the United States, membranes coated in fluorocarbon polymers, mixed with zirconia and other minerals, have replaced asbestos diaphragms as filters to separate brine in chlor-alkali facilities. Yibin installed its first fluorocarbon ion exchange membrane in 1991 (Yarime, 2003). These membranes are built with PTFE, which is a PFAS chemical. When exposed to high temperatures, PTFE gives off toxic fumes that are associated with respiratory problems and in extreme cases, the development of pulmonary edema (Sajid and Ilyas, 2017).

PFAS are a class of highly persistent, mobile, and hazardous chemicals characterized by at least one completely fluorinated carbon atom. These carbon-fluorine bonds are among the strongest bonds in chemistry making them extremely resistant to breaking down in the environment which leads to the accumulation of PFAS chemicals in people and the environment (National Institute of Environmental Health Services, 2021). The long-term persistence of PFAS chemicals has led them to be popularly known as “forever chemicals” (Allen 2018). PFAS are widely used in consumer and industrial products to impart grease resistance, water resistance, and non-stick properties. However, these PFAS chemicals can migrate into the air and water where they expose humans to a range of health effects and accumulate in the bodies of people and wildlife. Studies indicate that PFAS exposure is linked to elevated cholesterol levels, thyroid cancer and depressed immune system function, as well as fertility issues (ATSDR, 2020; EPA, n.d.). Over 12,000 chemicals belong to the PFAS class with new formulations currently being manufactured (EPA, 2021). Bans on specific PFAS, such as perfluorooctanoic acid (PFOA), have succeeded in reducing exposure to particular PFAS chemicals, but manufacturers often substitute with a different PFAS that has a similar toxic profile. The CDC found that approximately 97% of Americans tested have detectable blood levels of PFAS (Lewis et al., 2015).

PFAS use within the carbide PVC production process in China is calculated by attributing a common membrane coating composition with the average lifespan of membranes (Brinkmann et al., 2014). Membranes are sprayed with a compound created with a combination of alcohols, Triton X-100, Zirconium Oxide, and PFAS (North Carolina Division of Air Quality, 2019). This is related to PVC flooring by the amount of chlorine processed by a given meter squared of membrane, the amount of PFAS sprayed on that membrane, and a lifespan of 4 years (Brinkmann et al., 2014).

To assess PFAS carbon emissions, we utilize the CML2001 Methodology from Stropnik et al. (2019) to capture the emissions from manufacturing of PFAS. The transportation of the PFAS to the PVC manufacturing plant in Dongyuan Province, China, and the manufacturing of the PFAS were not accounted for in carbon emission estimates due to a lack of academically verified literature. After manufacture, the PFAS is transported by rail to Yibin (1974 km) and then by truck to the Yibin plant (69 km).

Mercury

Mercury is a highly toxic liquid metal that exists in three different chemical forms, each with differing toxicities and mobilities: elemental (liquid mercury), inorganic mercury and organic mercury (methylmercury). The elemental form of mercury has been used since the 1800s to separate brine into chlorine and caustic soda. Most chlor-alkali plants stopped using liquid mercury in chlor-alkali cells in recent decades, but some remain in operation in eastern Europe, Russia, India, and even the United States (Westlake's chemical plant in New Martinsville, West Virginia). Mercury cell technology accounts for an estimated 1% of all chlorine production worldwide (HBN 2019).

Mercury is used in the Chinese carbide PVC production process. After chlorine is separated from brine, it is combined with a carbon source to produce vinyl chloride monomer. Mercuric chloride salts are used as catalysts in the reaction of chlorine with coal to produce vinyl chloride monomers (VCM). These catalysts are prepared by reacting mercury with chlorine to form crystals of mercuric chloride. In most of the world, this practice, called the calcium carbide method of producing VCM, has vanished. The last plant in the U.S. - Borden Chemicals in Ascension Parish, Louisiana - closed in the 1990s. But in China, the reliance on this method is increasing to meet the production of cheap coal-based PVC. According to industry experts, this method accounts for about 80% of the total production in China (20.4 million tons of 25.18 million tons of VCM in 2019).[13]

The use of mercury in the production of vinyl chloride monomers not only poses a health risk to workers, but also to populations both proximate and distant to these plants as mercury vapors can be transported long distances in the atmosphere (Selin 2009; Zhang et al., 2014). Inorganic mercury is highly volatile and can be aerosolized in the production process, exposing workers to gaseous elemental mercury - known to cause lung damage in the form of chemical pneumonitis and bronchiolitis (Asano et al., 2000). Moreover, this gaseous elemental mercury can escape into the atmosphere, where it can be transported over long distances and redeposited in terrestrial environments far from the point source of pollution (Selin, 2009). In aquatic environments, inorganic mercury can be transformed into methylmercury, a potent neurotoxin that readily accumulates in the bodies of organisms and magnifies in concentration up the food

[13] Du, Daisy, and Noam David Stern, Analysis of the Chinese PVC Industry, China-Direct.biz (Shanghai), March 2021. https://mst.dk/media/220519/analysis-of-the-chinese-pvc-industry.pdf

chain (Diaz, 2021). Dietary exposure to methylmercury from consumption of contaminated fish is particularly dangerous for pregnant women and children because of adverse effects on neurological development. Chronic low-dose exposure to methylmercury has also been found to adversely affect the cardiovascular and immune systems (UNEP 2018).

The United Nations (UN) Environmental Programme (UNEP) estimates that use of mercury as a catalyst in the production of vinyl chloride monomers accounts for 58.2 tons of annual anthropogenic mercury emissions (UNEP, 2018). The World Bank found in 2014 that on average, 86.9 grams of mercury is consumed per ton of VCM/PVC production, or 86.9 tons mercury per million tons of PVC.The Bank projected that by 2020, China's VCM producers would be using catalysts with lower amounts of mercury which would reduce consumption to 49 grams per ton. Given Yibin's production capacity of 500,000 tons, and these rates of consumption, the plant consumes between 27 and 48 tons of mercury per year, most of which is released into the air, water, solid waste or as a trace contaminant in finished PVC products.[14]

The production and use of mercury catalysts to generate VCM in China releases mercury into the air. The United Nations Environment Programme provides an emission factor of 45 kilograms of mercury per ton produced in mercury smelters in China. The RECAST study further estimates that a plant comparable to Yibin released 2.4 grams of mercury air emissions per ton of VCM production.

In 2021, the Yibin plant exported 6,592 metric tons, 820 kilograms of vinyl flooring to the United States. At least 32.75% of the weight is PVC, based on the industry EPD for vinyl tile flooring. This requires the production of at least 2,200 tons of VCM at Yibin. According to the above referenced estimated rates, the production of these floors for U.S. consumption in 2021 consumed between 107 and 191 kilograms of mercury, of which at least five kilograms were released into the air of Yibin.

Subsequent mercury losses occur from the disposal and recycling of spent catalyst. The fate of this waste is largely unquantifiable. Lin (2016) notes, "Significant knowledge gaps exist in China for the catalyst recycling sector. Although more than half of the mercury used is recycled, this sector has not drawn enough attention. There are also more than 200 tons of mercury that had unknown fates in 2011."

[14] Detection method of total mercury content in PVC resin by using calcium carbide process. 2011. https://patents.google.com/patent/CN102226765A/en

An extensive literature review did not lead to any conclusive sources of carbon emission estimates for the extraction and transportation of mercury to the Yibin plant. As such, we were not able to account for these carbon emissions in our estimates.

Ethylene Dichloride

Toxic ethylene dichloride (EDC) is generated as an intermediary compound in the ethane to ethylene PVC production process in the United States. EDC is a flammable substance used primarily in the production of VCM but also used as a solvent and gasoline additive in other applications (Yuan et al. 2020). Ethylene dichloride is heated to high temperatures (cracked) to generate vinyl chloride monomer.

Epidemiological studies of workers exposed to EDC have shown that acute occupational exposure can result in neuropsychological impairment including decreased motor function and attention deficits (Bowler et al. 2003). Numerous studies have observed adverse health effects from low-dose exposure to EDC in workers and residents in close proximity to petrochemical cracking facilities including liver fibrosis, (Yuan et al. 2020). Inhalation of volatile EDC can cause respiratory distress, nausea, vomiting, and cardiac arrhythmia (EPA IRIS). The International Agency for Research on Cancer lists ethylene dichloride as a probable human carcinogen.

The cracking process also emits ozone-depleting toxic chlorinated carbon compounds including dioxins and polychlorinated biphenyls. All of these releases pose health hazards to fenceline communities, and some are highly damaging to earth's climate and protective stratospheric ozone layer.

Vinyl Chloride Monomer

Vinyl chloride monomer (VCM), the precursor to PVC, is recognized by authoritative bodies as a known human carcinogen (IARC 2007). Exposure to VCM is associated with the development of a rare form of cancer, angiosarcomas of the liver, and hepatocellular carcinomas (Sherman 2009; Brandt Rauf et al. 2012). Moreover, there is evidence that exposure to vinyl chloride increases the risk of developing liver cirrhosis (IARC 2007). VCM is an odorless gas at room temperature and occupational exposure can occur through inhalation when ethylene dichloride is cracked to produce vinyl chloride and when VCM is polymerized to produce PVC resin. Epidemiological studies of workers in PVC plants provided strong evidence of the carcinogenicity of this man-made compound and research in animal models has provided evidence of the genotoxicity of vinyl chloride (IARC 2007).

Concurrent exposures to both ethylene dichloride and vinyl chloride augment the adverse health risks for workers exposed to these toxic compounds. While in the United States, there have been improvements in occupational safety standards in PVC manufacturing, there are still concerns of high occupational exposure to VCM in other countries around the world.

Vinyl chloride emissions into ambient air from production facilities also endanger the health of fenceline communities. High concentrations of vinyl chloride have been detected in the ambient air near landfills where PVC is disposed of and in the leachate and groundwater surrounding these facilities (Kielhorn et al. 2000). Finally, detectable levels of vinyl chloride are sometimes present in finished PVC products such as vinyl flooring (Kielhorn et al. 2000).

4. Conclusions & Recommendations

Irrespective of its geographic origin, all PVC flooring sold in the United States has been produced using some of the most toxic chemicals known to humans. Toxics like mercury, PFAS, and asbestos - long thought to be completely phased out of use in the United States because of its status as a known carcinogen - are still used today to produce PVC flooring, as well as other PVC-based products like pipes, clothing, and vinyl siding. Not only are the toxics used in flooring production detrimental to humans and the environment, but also manufacturing PVC is a highly energy intensive process that emits potent climate-warming greenhouse gasses into the atmosphere.

As humans stand on the precipice of an irreversible and catastrophic climate emergency, it is imperative that decarbonization initiatives consider not only the carbon footprint of materials used in our built environment but also the toxic chemicals that go into producing these materials. The carbon and chemical pollution created by manufacturing PVC flooring impacts the entire planet; endangering workers, front and fenceline communities, and ultimately every living being on earth. Flooring manufacturers, consumers, designers, and everyday individuals all have a role to play in helping to reduce and eventually phaseout the use of PVC products in our built environment. Below we provide specific recommendations for different stakeholders.

Flooring Manufacturers

1. Embrace transparency by disclosing all product ingredients in EPDs including those that are consumed in the process of PVC manufacturing like mercuric chloride
   a. Detail all assumptions in EPDs about product lifespan, recyclability, use, and maintenance
2. Immediately adopt policies that phase out the use of asbestos, mercury, and PFAS chemicals in PVC production
3. Avoid regrettable substitution and assess any alternative chemicals for safety using GreenScreen for Safer Chemicals or ChemFORWARD databases

Institutional Purchasers and Consumers

1. If possible, keep the flooring you have in place or refinish existing hardwood
2. Consider purchasing healthier flooring like linoleum or ceramic tile instead of PVC flooring
   a. CEH has compiled a purchasing guide that details healthier flooring options and is accessible at the following link: CEH Healthier Flooring Purchasing Guide
   b. In addition, more healthy flooring options can be found at: Greenhealth Approved Flooring
3. Avoid buying other PVC-based products where you can – some examples include vinyl siding for homes, vinyl window treatments, and vinyl blinds
4. Sign up for our email list to stay up to date on the latest news about CEH's work to protect people from toxic chemicals at CEH.org

Designers

1. Educate your clients about the carbon footprint and toxics concerns associated with PVC flooring
2. Reject the latest trend toward luxury vinyl tile
3. Wherever possible, recommend flooring with the lowest carbon *and* toxics footprint, to your clients
4. For more information on healthier flooring options visit:
   a. CEH Healthier Flooring Purchasing Guide
   b. Greenhealth Approved Flooring

Appendix A - Supplementary Information

Table A1. PVC Flooring Cradle-to-Site Carbon LCA (30 years).

	Sheet Flooring			Tile Flooring			
Value	**Yibin, China**	**Occidental, U.S.**	**PVC Flooring EPD (Nox)**	**Yibin, China**	**Occidental, U.S.**	**PVC Flooring EPD (RFCI)**	**Units**
Value (kg/m2 of flooring)	24.65	9.58	8.80	34.65	16.32	12.81	CO_2e kg (cradle-to-site [A1, A2, A3, A4])

Table A2. Rate of use of toxics in manufacturing PVC flooring. Results for vinyl sheet flooring and vinyl tile flooring on a kg per m2 of flooring basis.

Toxic (Production Process)	Sheet Flooring (kg/m2)	Tile Flooring (kg/m2)
PFAS (China chlor-alkali)	0.00000004	0.00000005
Asbestos (U.S. chlor-alkali)	0.00002959	0.00003624
Mercury (China VCM)	0.00016532	0.00020251

Table A3. PVC Flooring Cradle-to-Site Carbon Analysis by LCA System Boundary (30 Years).

LCA System Boundaries		Sheet Flooring			Tile Flooring			Units
Code	**Description**	**Yibin, China**	**Occidental, U.S.**	**PVC Flooring EPD (Nox)**	**Yibin, China**	**Occidental, U.S.**	**PVC Flooring EPD (RFCI)**	
A1 - A3	Raw Material Supply, Transportation of Raw Materials, & Manufacturing	24.19	9.38	7.68	34.19	16.12	11.90	CO_2e kg (cradle-to-site [A1, A2, A3, A4])
A4	Transportation to Site	0.46	0.20	1.12	0.46	0.20	0.91	
Total		**24.65**	**9.58**	**8.80**	**34.65**	**16.32**	**12.81**	

Figure A1. Yibin Manufacturing Site Supply Chain

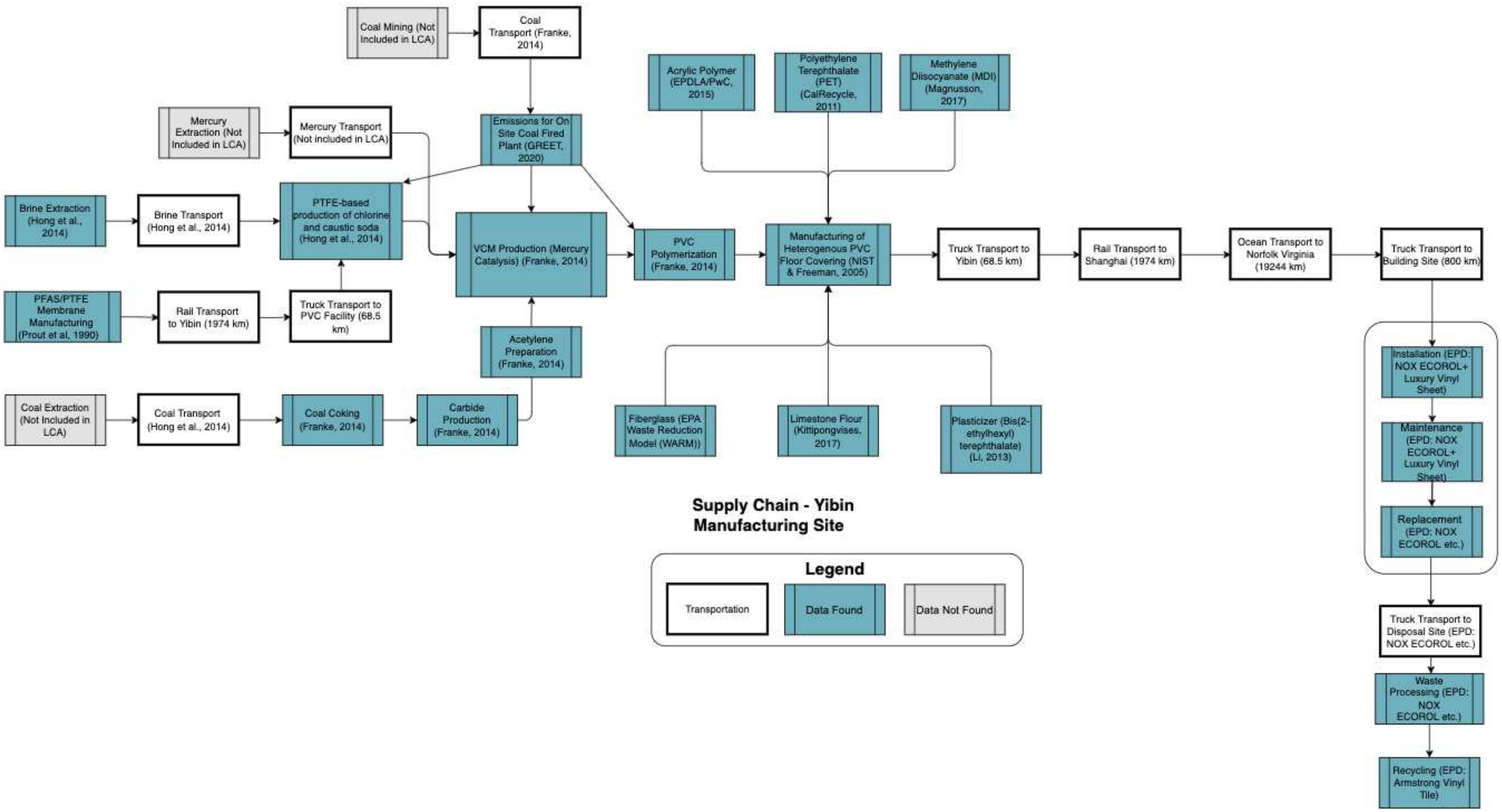
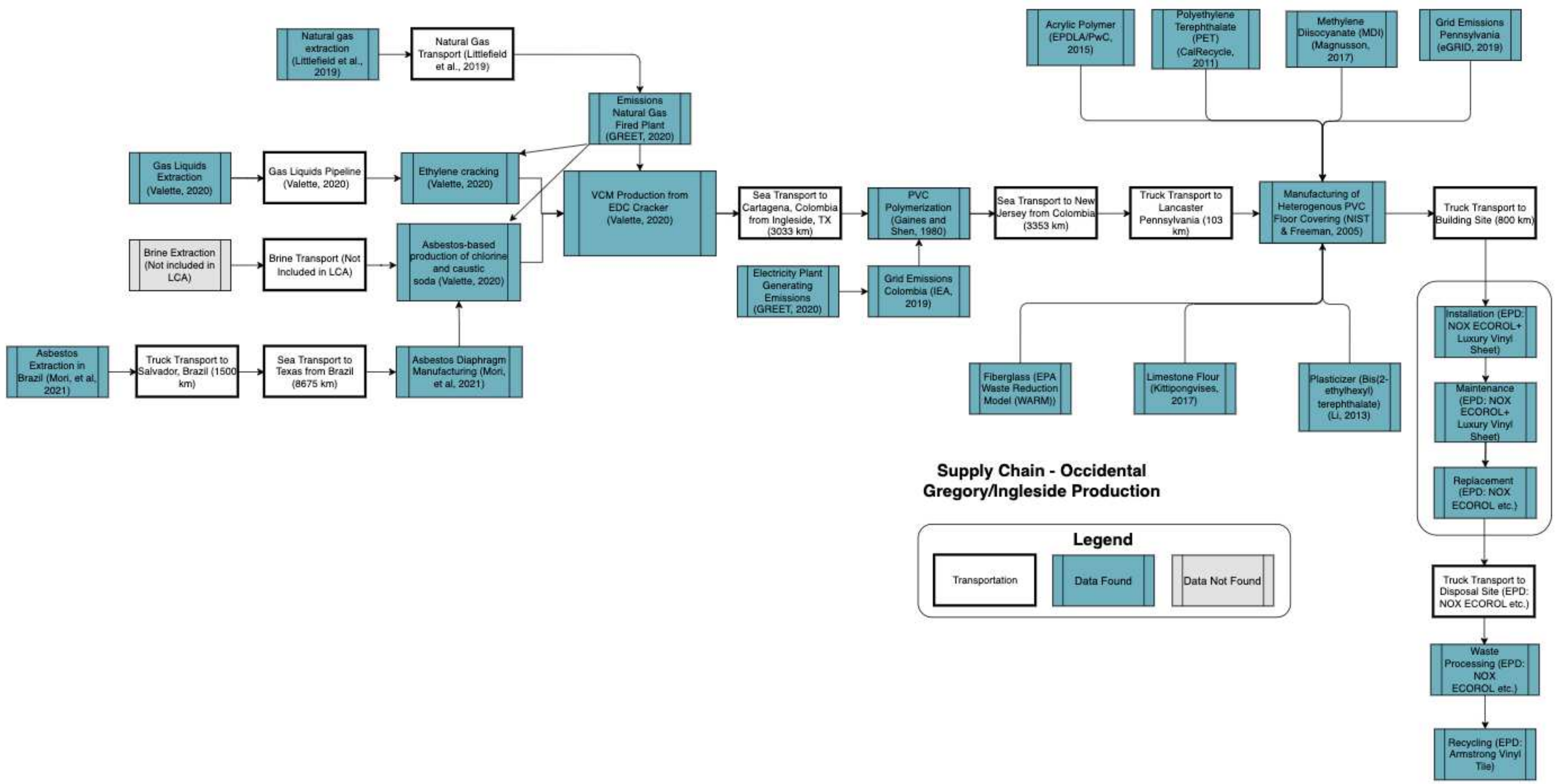


Figure A2. Occidental Gregory/Ingleside Manufacturing Site Supply Chain



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