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Deep Decarbonization Roadmap for the PVC Industry in the U.S.

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Global Efficiency Intelligence

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Executive Summary

The industry sector accounts for over one-third of global anthropogenic greenhouse gas (GHG) emissions. The chemical industry is the third largest CO_2-emitting industry sector. The emissions from the chemical industry must be reduced sharply for the world to reach the target of the Paris Climate Agreement: to limit global warming to "well below" 2 ℃.

Polyvinyl chloride (PVC) is the world's third-most widely produced synthetic plastic polymer (after polyethylene and polypropylene). Approximately, 44 million metric tons (Mt) of PVC are produced each year globally. In 2019, the U.S. production volume of PVC was around 7.2 Mt. The PVC resin manufacturing process (excluding the feedstock chemical production) accounts for around 11% of total carbon dioxide (CO_2) emissions from the plastics and resins manufacturing sector in the U.S. With the world's growing population and the increasing need for housing and other products that use PVC, the PVC demand will likely continue to increase in the coming years and decades. This means the total energy use and GHG emissions of the PVC industry are likely to continue to increase if the current production methods are not decarbonized substantially. The United States government has a target of reducing emissions by 50%–52% below 2005 levels by 2030 and, as a part of the Paris Agreement, pledged to reach net zero emissions economy-wide by no later than 2050. The U.S. PVC industry will need to take significant actions to reduce its GHG emissions and move toward carbon neutrality by 2050.

This study focuses only on the deep decarbonization of the PVC resin manufacturing industry. The upstream (raw material production) and downstream (manufacturing of various PVC final products) are not included in this study. There are five PVC resin manufacturing companies in the US operating 14 PVC resin manufacturing plants. The U.S. PVC resin manufacturing industry used around 52.5 petajoules (PJ) of energy in 2021. This translates to around 3.9 million tonnes (Mt) of CO_2 emissions in that year. Only 20% of the total energy used in the U.S. PVC resin manufacturing industry is electricity, and the remaining 80% of energy is the fuel used in boilers, cogeneration systems, and furnaces.

The goal of this study is to develop a roadmap for deep decarbonization of the U.S. PVC resin manufacturing industry. In this study, we analyzed the current status of the PVC resin manufacturing industry and developed scenarios up to 2050 to analyze different decarbonization options and pathways that can help substantially reduce CO_2 emissions of the PVC resin manufacturing industry in the U.S. We included five major decarbonization options in our analysis, which are: 1) energy efficiency, 2) fuel switching to clean hydrogen, 3) limited-scale fuel switching to sustainable biofuels, 4) electrification of steam boilers, and 5) electrification of furnaces.

Our analysis up to 2050 shows that under the business-as-usual (BAU) scenario, which assumes no significant changes in current policies and market practices, the total CO_2 emissions from the U.S. PVC resin manufacturing industry will decrease from 3.9Mt CO_2 per year in 2021 to 3.1 Mt CO_2 per year in 2050, a 21% decrease. This is while PVC resin production in the U.S. is assumed to increase by 20% during the same period. This is driven by the incremental improvement in energy efficiency and electricity grid decarbonization (75% clean electricity in 2050 [1]). Under our Toward Zero Emissions scenario, however, the annual CO_2 emissions from the U.S. PVC resin manufacturing will decrease to about 1 Mt CO_2 per year in 2050, around 75% reduction compared to the 2021 level (Figure ES 1). This reduction in CO_2 emissions is equal to emissions from around 750 thousand passenger cars per year.

1. In our base case modeling analysis, we assumed that the electricity from the grid in the states where PVC plants are located will be 75% from clean sources (renewables and nuclear) in 2050. However, other scenarios with less and more ambitious assumptions about grid emissions factor in 2050 are also included in the Appendix. It should be noted that the U.S. government also has set a goal to reach 100% CO_2-free electricity by 2035 (The White House 2021)

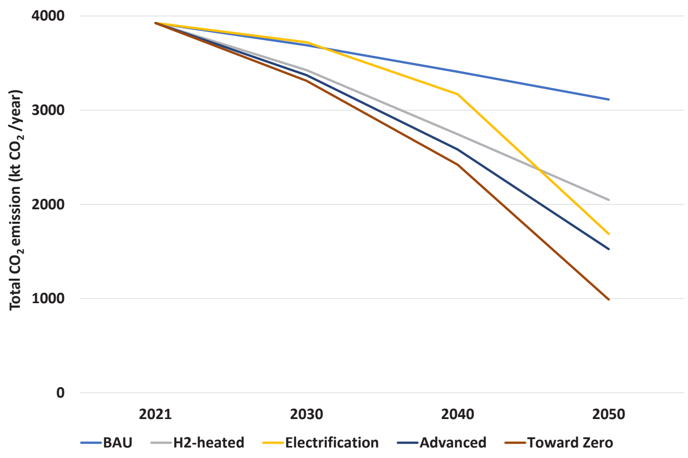

Figure ES1. Total CO_2 emission in the U.S. PVC resin manufacturing industry under various decarbonization scenarios (Source: this study)

The Electrification scenario, which assumes partial electrification of steam boilers and furnaces in the PVC resin manufacturing industry, results in a substantial annual CO_2 emissions reduction in 2050. This is because boilers and furnaces account for the majority of energy used in the PVC resin manufacturing industry, and electrification of those coupled with a low-carbon electricity grid in 2050 will result in substantial CO_2 emission reduction. It should be noted that while electric furnaces for the PVC resin manufacturing industry are still emerging technologies, electric boilers are fully commercial technologies and are available off-the-shelf. The main challenge to electrification adoption in the industry is the relatively lower price of natural gas in the U.S. compared to electricity prices. As the price of renewable energy production drops even further over time and the price of fossil fuels (e.g., natural gas) increases both because of market forces (such as the events in 2021 and 2022) or because of the introduction of some type of carbon price in the U.S. in coming years, the electrification technologies can become cost-competitive compared to the conventional combustion technologies.

Figure ES2 shows the contribution of each decarbonization option to the CO_2 emissions reductions in the Toward Zero Emissions scenario for the U.S. PVC resin manufacturing industry in 2050. Electrification of boilers makes the largest contribution to CO_2 emissions reduction, followed by energy efficiency and use the hydrogen for process heating. The contribution of furnace electrification and sustainable biofuels for heating and thermal processes is projected to be smaller because of our conservative assumptions because of techno-economic reasons, as discussed later in this report.

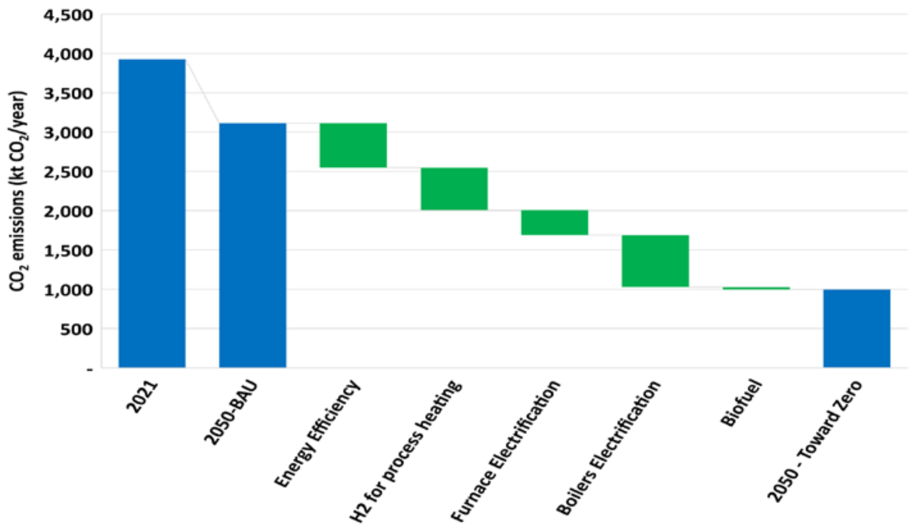

Figure ES2. Impact of CO_2 emissions reduction options in the Toward Zero Emissions scenario for the U.S. PVC resin manufacturing industry in 2050 (Source: this study)

Our Toward Zero Emissions scenario is technologically achievable with commercially available technologies and measures except for electric furnaces technologies which are emerging technologies requiring more research, development, and demonstration (RD&D) support. The U.S. Department of Energy can play an important role in this RD&D effort. In addition to decarbonization options included in our modeling analysis and discussed above, there are other options for reducing CO_2 emissions in the PVC resin manufacturing industry and its upstream and downstream value chain, such as bio-based feedstock and PVC recycling. Some of these decarbonization measures are also qualitatively discussed later in this report.

U.S. PVC manufacturing companies play a pivotal role in driving the decarbonization of the industry by proactively adopting and investing in low-carbon technologies and practices. Companies should prioritize energy efficiency improvements, adopt fuel-switching options, such as transitioning to clean hydrogen, and implement electrification of steam boilers and furnaces. Early adoption of these technologies can provide a competitive edge and help companies stay ahead of potential future regulations. Additionally, PVC manufacturers should collaborate with stakeholders, including policymakers, research institutions, and industry peers, to identify and address barriers to decarbonization. This can involve sharing best practices, participating in joint R&D initiatives, and engaging in public-private partnerships to advance the necessary infrastructure for clean energy sources (clean hydrogen and low-carbon electricity). By taking these actions, U.S. PVC manufacturing companies can demonstrate their commitment to a sustainable future while enhancing their global competitiveness.

The U.S. government has a critical role to play in facilitating the decarbonization of the U.S. PVC industry. Industrial decarbonization policies should focus on creating an enabling environment for technology adoption, infrastructure development, and market transformation. This can be achieved through a combination of measures, such as offering financial incentives for the deployment of low-carbon technologies, funding research and development (R&D) for emerging technologies like electric furnaces. Additionally, the government can promote the use of clean energy sources, such as clean hydrogen and low-carbon electricity, by investing in the necessary infrastructure and supporting the scaling up of production capacities. The Inflation Reduction Act (IRA) aims to enhance the clean energy production and infrastructure. By fostering a supportive policy landscape, the government can accelerate the decarbonization of the PVC industry while fostering economic growth and innovation.

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1 Introduction

The industrial sector accounts for more than one-third of global anthropogenic greenhouse gas (GHG) emissions. Within that, the chemical industry is the third largest CO_2-emitting industry sector, after the steel and cement industry (IEA 2019). The emissions from the chemical industry must be reduced sharply for the world to reach the target of the Paris Climate Agreement: to limit global warming to “well below” 2 ℃.

The United States government has a target of reducing emissions by 50%–52% below 2005 levels by 2030 and, as a part of the Paris Agreement, pledged to reach net zero emissions economy-wide by no later than 2050. The U.S. also has set a goal to reach 100% CO_2-free electricity by 2035, which will substantially help the deep decarbonization of industries such as steel, aluminum, and the Chemical sector (The White House 2021). The Inflation Reduction Act, signed into law by President Biden in August 2022, includes $369 billion to address climate change (CAP 2022). The chemical industry and, in particular, the Polyvinyl chloride (PVC) industry has a key role to play in achieving the U.S. climate targets.

Polyvinyl chloride (PVC) is the world’s third-most widely produced synthetic plastic polymer (after polyethylene and polypropylene). About 44 million metric tons (Mt) of PVC are produced each year. In 2019, the U.S. production volume of PVC was around 7.2 Mt (Statista 2019). With the world’s growing population and increasing need for water and electrical infrastructure, housing, and other products that use PVC, the PVC demand will likely continue to increase in the coming years and decades. This means the energy use and greenhouse gas (GHG) emissions of the global PVC industry are likely to continue to increase, particularly in developing countries, since increased demand is outpacing the incremental decreases in energy and carbon dioxide (CO_2) emissions intensity of PVC production that is happening under the current incremental improvement rate.

As more countries and companies commit to carbon neutrality by 2050, the PVC industry also needs to develop a strategy for the deep decarbonization of this sector. Therefore, there is a need for the development of a roadmap for the deep decarbonization of the PVC industry. This study focuses only on the deep decarbonization of the PVC resin manufacturing industry. The upstream (raw material production) and downstream (manufacturing of various PVC final products) are not included in this study.

This report outlines a deep decarbonization roadmap for the U.S. PVC resin manufacturing industry that is data-driven to achieve mid-century low CO_2 emissions. In addition, it includes the milestones of what the industry can accomplish in 2030, 2040, and 2050.

2 Overview of the PVC Resin Manufacturing Industry

PVC is part of the vinyl chain, which also comprises the precursors ethylene dichloride (EDC) and vinyl chloride monomer (VCM). The total global production volume of PVC in 2018 was around 44 Mt (Statista 2021). China accounted for approximately half of the global PVC production (Daisy Du and Noam David Stern 2021; SP Global 2021). PVC resin grades can be used for rigid and flexible applications; rigid is consistently the dominant consumer, but in parts, the two are closely aligned. The majority of rigid PVC is used heavily in the construction industry for pipe and fittings such as drain-waste-vent pipes, sewer, water pipes, conduit (electrical, telecommunications), and irrigation pipes. Rigid grades of PVC are also utilized in the building and housing markets for profile applications such as doors, window frames, exterior cladding, fencing, decking, and luxury vinyl tiles. A smaller volume of rigid PVC is manufactured for security packaging, credit cards, medical devices, electrical components, and more.

PVC resin can be used in flexible applications with the addition of plasticizers. In this form, it is also used in wire and cable insulation, blood bags, medical tubing, imitation leather, signage, inflatable products, roofing membranes, and many applications where it replaces rubber. This versatile advantage, along with attributes like durability, nonflammability, resistance to chemicals and oil, mechanical stability, and ease of processing and molding, indicates that PVC remains a competitive and attractive option for many applications in the construction and infrastructure, agriculture, electrical products, and healthcare industries. Hence, PVC will remain a significant thermoplastic over the long term.

Since the construction industry plays a key role in the PVC market, demand for PVC is closely aligned with global gross domestic product (GDP) growth and economic development. Stronger PVC consumption is usually more concentrated in the developing economies in Asia, such as China and India (Tomas net 2022). The common drivers of PVC consumption for high-demand locations include a large population base that has considerable spending on infrastructure. Another factor is the size and stage of development of the country's agriculture sector. India, for instance, requires significant systems to irrigate its farmlands and therefore has a great, sustainable demand for PVC pipes and fittings.

The vinyl industry is a mature sector with a long history. Technology, production volume, environmental footprint, and cost have improved over time with upgrades in safety and product quality. Technological innovation continues to occur and is focused mainly on cost competitiveness since vinyl production is a truly global business, and manufacturers must be competitive both within their regions and across the world.

PVC production is more commonly based on ethylene feedstock, except in mainland China, where coal-based calcium carbide as feedstock for acetylene production dominates. In the ethylene process, ethylene dichloride (EDC) is produced by direct chlorination from chlorine and ethylene. In a later step, it is cracked to produce a vinyl chloride monomer (VCM). The production of VCM also results in the release of by-product hydrogen chloride (HCl), which is typically recycled to produce more EDC by oxychlorination with additional ethylene. VCM is then polymerized to produce PVC, with residual VCM also being recycled in the PVC synthesis process. Figure 1 shows a simplified flow diagram of the VCM and PVC resin manufacturing process (Li et al. 2014).

In the acetylene process, which is based on coal-based calcium carbide, no EDC step is involved; instead, VCM is produced directly from acetylene. China is now the only market with major acetylene-based PVC facilities. Around 80% of the total PVC produced in China is from the acetylene process (Daisy Du and Noam David Stern 2021; SP Global 2021). As mentioned above, China accounted for around half of the global PVC production. Therefore, with 80% of its production being from the acetylene process, this process accounts for around 40% of global PVC production.

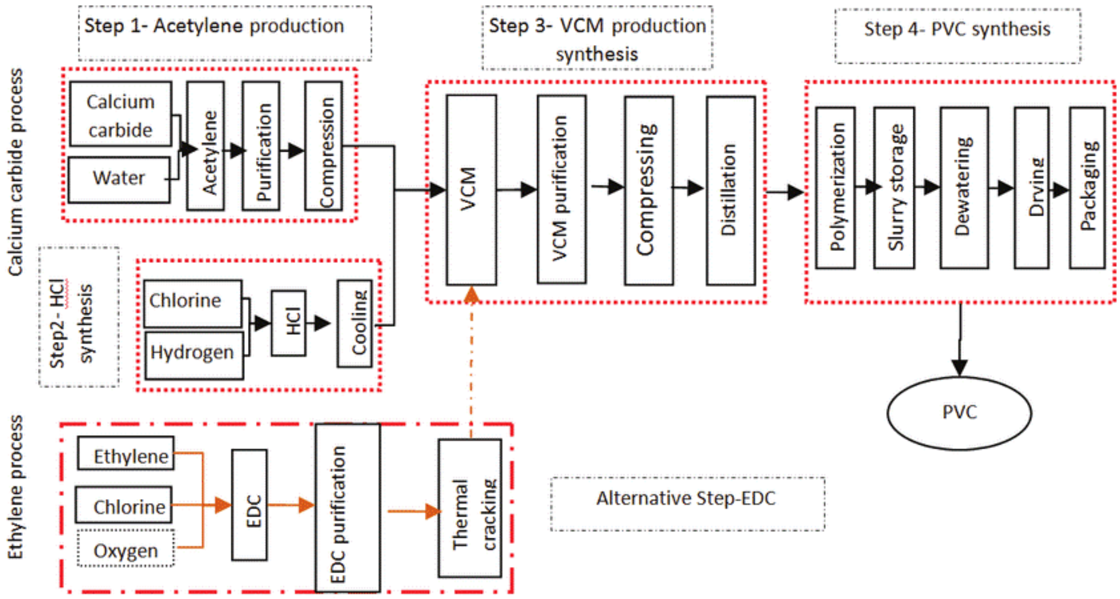


Figure 1: The simplified flow diagram of the VCM and PVC resin manufacturing process (Source: Li et al. 2014) (Note: most of world PVC production uses ethylene as raw material, except in China where calcium carbide is the main raw material.)

2.1. The Status of the U.S. PVC Resin Manufacturing Industry

There are five major PVC resin manufacturing companies in the U.S., including 1) Formosa Plastics Corporation, 2) Westlake Chemical Corporation, 3) Shintech, 4) OxyChem (OxyVinyls), and 5) Vestolit (Orbia). Figure 2 illustrates the U.S. PVC resin manufacturing industry's annual production from 2010 to 2019 in kilotonnes (kt) per year.

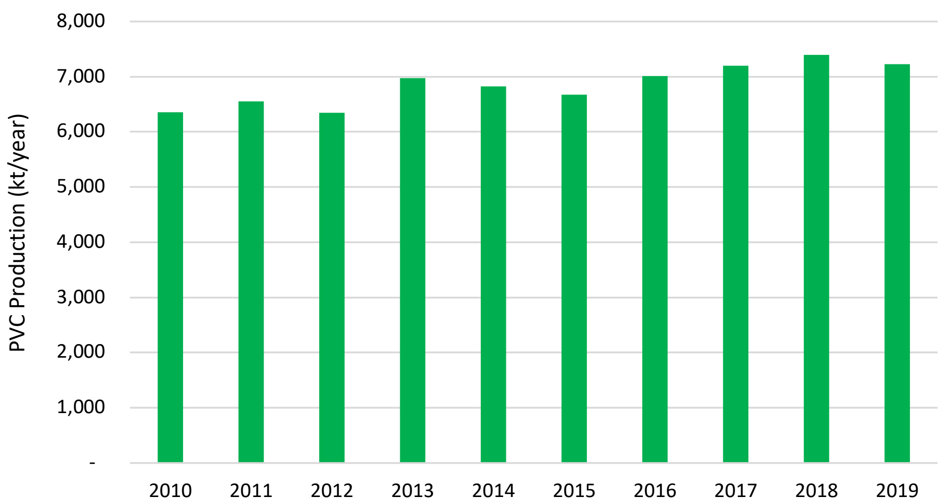


Figure 2: U.S. PVC resin manufacturing industry historical production trend (2010-2019) (Source: Statista 2019)

The production facilities of PVC resin manufacturing companies in the U.S. are provided in Table 1. The share of each company from total PVC production (including both suspension resin and dispersion resin) in the US is given in Figure 3.

Table 1: Production facilities of the main PVC producers in the U.S.

Company name	Facility Name/locations
Formosa Plastics Corporation	1) Point Comfort, Texas 2) Baton Rouge, Louisiana
Westlake Chemical Corporation	1) Aberdeen, Mississippi 2) Calvert City, Kentucky 3) Geismar, Louisiana 4) Plaquemine, Louisiana
Shintech	1) Freeport, Texas 2) Addis, Louisiana 3) Plaquemine, Louisiana
OxyChem (OxyVinyls)	1) Pasadena, Texas; 2) Deer Park, Texas 3) Pedricktown, New Jersey
Vestolit (Orbia)	1) Henry, Illinois 2) Pedricktown, New Jersey

Source: HIS Markit 2020, Formosa Plastics Corporation 2022, Westlake 2022, Shintech 2022, Oxychem 2022, and Vestolit 2022

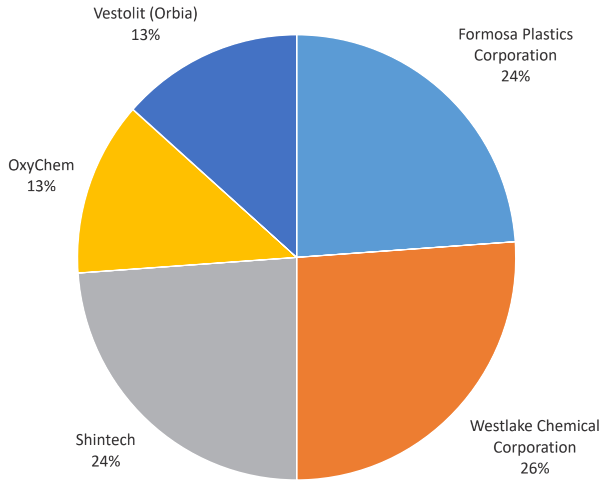


Figure 3: Share of each company from the total production capacity of the U.S. PVC resin manufacturing industry in 2021

(Source: HIS Markit 2020, Formosa Plastics Corporation 2022, Westlake 2022, Shintech 2022, Oxychem 2022, and Vestolit 2022)

2.2. Energy Use and CO_2 Emission in the U.S. PVC Resin Manufacturing Industry

The PVC resin manufacturing industry is an energy and emission-intensive industry. The three main types of energy used in the PVC resin manufacturing industry are steam, fuel for furnaces, and electricity.

We used the detailed energy use breakdown for the PVC resin manufacturing industry from a recent Dutch study (Semeijn and Schure 2020) to disaggregate the energy intensity of the U.S. PVC resin manufacturing industry given by the U.S. DOE (2017). Figure 4 shows the estimated amount and share of different energy types used in a typical PVC resin manufacturing plant in the U.S. The steam system energy use accounts for about 42% of total final energy consumption, while fuel used in furnaces and electricity use account for around 38% and 20%, respectively.

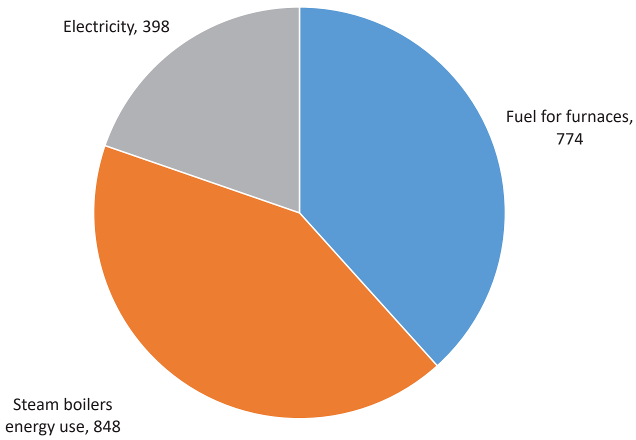


Figure 4: Estimated share and value of different energy use in a typical PVC resin manufacturing plant in the U.S. (values are in kWh/ton PVC)
(Source: estimated based on U.S. DOE 2017 and Semeijn and Schure 2020)

We used 2021 as the base year for this study. According to the historical production trend shown above, we estimated that the total production of PVC resin in the U.S. was 7.2 Mt in 2021. Based on historical production patterns and expert consultation, we assumed that PVC resin production in the U.S. will increase linearly by 20% between 2021 and 2050. Using the PVC resin production in 2021 and energy intensities shown in Figure 4, we estimated the annual energy use of the PVC manufacturing industry in the U.S. in 2021 (Table 2). The total final energy used in PVC resin manufacturing is 52.5 petajoules (PJ), which is around 9% of the total energy used in the plastics and resin manufacturing sector in the U.S. (US DOE 2021).

Table 2: Estimated energy use in the U.S. PVC manufacturing industry in 2021 (Source: this study)

Fuel use (PJ/yr)	Electricity use (GWh/yr)	Total final energy use (PJ/yr)
42	2,867	52.5

Based on the energy consumption shown above, the total CO_2 emission of the PVC resin manufacturing industry in the U.S in 2021 was estimated to be around 3,925 kt CO_2/year, and Figure 5 illustrates the share of those emissions from fuel and electricity. The emissions from the PVC resin manufacturing industry (excluding the feedstock chemical production) account for around 11% of total CO_2 emissions from the plastics and resin manufacturing sector in the U.S. (US EIA 2021).

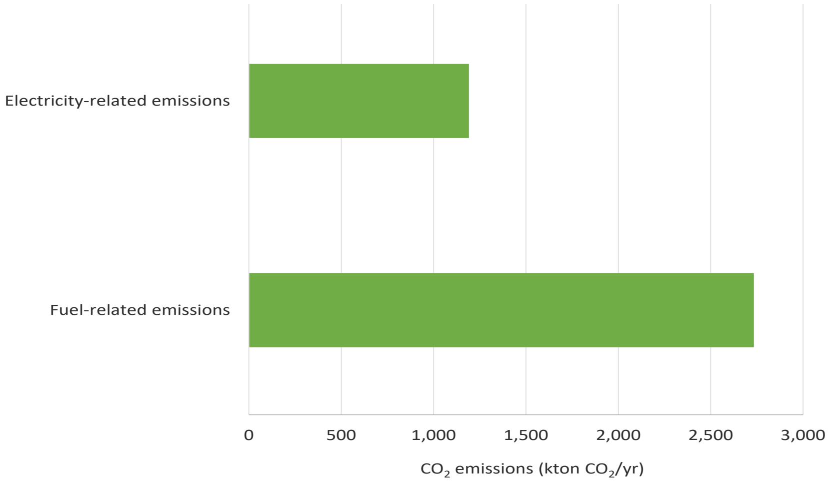


Figure 5: Fuel and electricity-related CO_2 emissions in the PVC resin manufacturing industry of the U.S. in 2021 (Source: this study)

3 Decarbonization Roadmap for the U.S. PVC Resin Manufacturing Industry

As previously stated, the boundary of this analysis was PVC resin manufacturing. The upstream and downstream processes of the PVC value chain were not included in our modeling analysis. The decarbonization options for the PVC resin manufacturing industry that are included in this analysis can be categorized into five main components, as shown below:

1. Energy efficiency
2. Fuel switching to clean hydrogen[2] in furnaces
3. Fuel switching to sustainable biofuels
4. Electrification of furnaces
5. Electrification of steam boilers

In addition, there are decarbonization technologies for upstream and downstream PVC manufacturing (e.g., feedstock substitution in upstream and recycling measures downstream) that can be adopted in the PVC value chain to reduce the final PVC product's carbon footprint. However, these upstream and downstream processes were not in our scope of analysis, and therefore the decarbonization options that can be implemented in those stages of the process are not included in our modeling analysis. We discuss these options briefly later in this report. An overview of a few key decarbonization options for the PVC production value chain is illustrated in Figure 6.

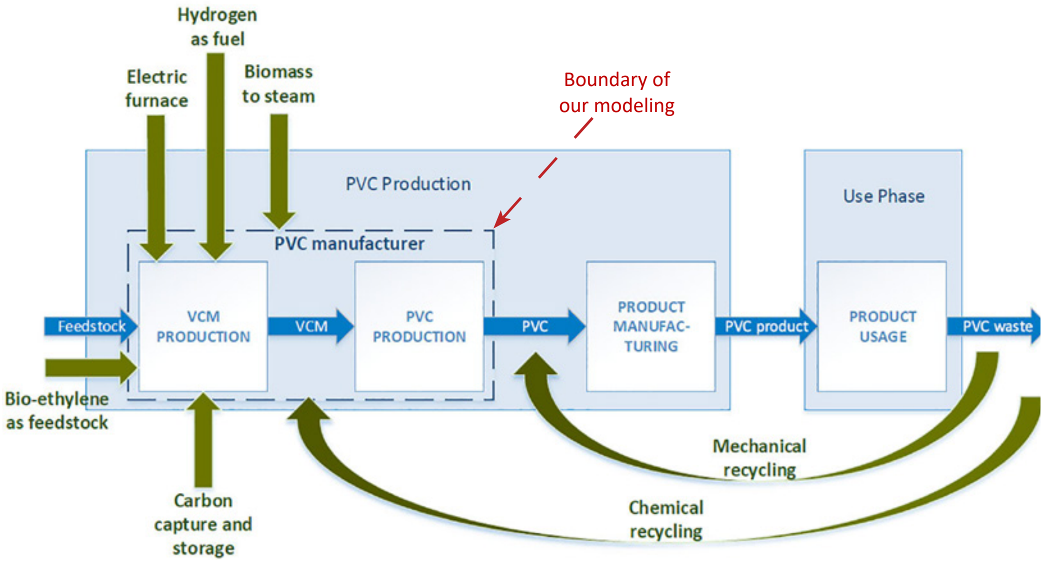


Figure 6: PVC production value chain, selected decarbonization options, and the boundary of this analysis (Source: Semeijn and Schure 2020)

In this study, the impact of the selected decarbonization options on energy use and emissions in the U.S. PVC resin manufacturing industry has been analyzed using a quantitative approach and scenario analysis.

2. US DOE's draft Clean Hydrogen Production Standard (CHPS) proposes a lifecycle GHG emissions target of 4 kg CO_2e per kilogram of hydrogen, which is in line with clean hydrogen production tax credit in the Inflation Reduction Act (US DOE 2022e).

3.1. Scenarios definition

To develop the decarbonization roadmap for the U.S. PVC resin manufacturing industry, we have defined five pathway scenarios as listed below. For more detailed information on the adoption rate of decarbonization options under each scenario, please see Appendix 1.

1) Business as Usual (BAU) scenario: It assumes a slow improvement in energy efficiency and slow adoption of commercially available decarbonization technologies, which is likely to happen with current business practices and current policies and regulations.

2) Electrification scenario: It assumes that furnaces and boilers of the PVC resin production facilities will be electrified gradually up to a substantial level in 2050. The energy intensity reduction is assumed at the BAU level.

3) Hydrogen-heated scenario: It assumes that the fossil fuel consumption for the EDC cracking furnaces of PVC production facilities will be gradually switched to clean hydrogen up to substantial levels in 2050. The energy intensity reduction is assumed at the BAU level.

4) Advanced scenario: It assumes a small share of fuel switching to clean hydrogen (lower than the H2-heated scenario). The electrification rate of furnaces will be lower than that in the electrification scenario, but the electrification of boilers is the same level as in the electrification scenario. It assumes a limited usage of biofuel in 2040 and 2050. It also assumes a more aggressive energy intensity reduction compared with the BAU.

5) Toward Zero Emission scenario: It assumes more aggressive fuel switching for both clean hydrogen and biofuel in 2040 and 2050 compared with the Advanced scenario and a higher rate of electrification. It assumes a more aggressive energy intensity reduction compared with the BAU scenario (see Appendix 1 for detailed assumptions).

Under all scenarios, as the base case, we assumed that the electricity from the grid in the states where PVC plants are located will be 75% from clean sources (renewables and nuclear) in 2050. However, should be noted that the U.S. government also has set a more ambitious goal to reach 100% CO_2-free electricity by 2035 (The White House 2021). Therefore, in addition of the base case analysis presented in the main body of the report, we have also presented a scenario that assumes 100% CO_2-free electricity in 2050 in Appendix 2.1. Table 3 provides a summary of the key decarbonization technologies assumed under each scenario.

Table 3: Key decarbonization options assumed in each scenario for the U.S. PVC resin manufacturing decarbonization roadmap

Decarbonization option	BAU scenario	Electrification scenario	H_2-heated scenario	Advanced scenario	Toward Zero Emission scenario
Energy Efficiency	X	X	X	X	X
Hydrogen as furnace fuel	-	-	X	X	X
Electric furnaces	-	X	-	X	X
Electric boilers	-	X	-	X	X
Biofuels as fuel	-	-	-	X	X

Note: The adoption rate of each decarbonization option may vary across scenarios.

Table 4 shows the energy intensity and CO_2 intensity under each different scenario estimated in this study for 2021 - 2050. It includes the energy and CO_2 intensities for both fuel and electricity, as well as the total final energy intensity and total CO_2 intensity for the U.S. PVC resin manufacturing industry.

Table 4: Energy and CO_2 intensities in the U.S. PVC resin manufacturing industry under each scenario, 2021-2050 (Source: this study)

	Unit	2021	BAU scenario			Electrification scenario			H_2-heated scenario			Advanced scenario			Toward Zero Emission scenario		
			2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Electricity intensity	kWh/t PVC	398	378	358	338	477	857	1339	378	358	338	411	539	742	411	618	930
Fuel intensity	GJ/t PVC	5.8	5.6	5.3	5.0	5.1	3.2	0.7	5.6	5.3	5.0	4.9	3.4	1.9	4.9	3.1	1.1
Total final energy intensity	GJ/t PVC	7.3	7.0	6.6	6.2	6.9	6.2	5.6	7.0	6.6	6.2	6.4	5.4	4.6	6.4	5.3	4.5
Electricity-related CO_2 intensity	kg CO_2/t PVC	165	121	77	37	153	185	147	121	77	37	132	116	82	132	133	102
Fuel-related CO_2 intensity	kg CO_2/t PVC	380	361	342	323	333	205	48	326	260	200	309	201	95	301	164	12
Total CO_2 intensity	kg CO_2/t PVC	545	482	419	360	486	390	195	448	337	237	441	318	176	433	298	114

3.2. Decarbonization Pathways for the U.S. PVC Resin Manufacturing Industry

We forecasted the total final energy use and CO_2 emissions of the PVC resign manufacturing industry in the U.S. up to 2050 under different scenarios by applying varying levels of different decarbonization technologies. The results of our analysis are shown in Figures 7-8. In the BAU scenario, the total final energy use of the U.S. PVC resin manufacturing industry will increase by about 2% between 2021 and 2050. This is while PVC resin production in the U.S. is assumed to increase by 20% during the same period. However, due to the moderate energy efficiency improvement and decarbonization of the grid up to 2050, the annual CO_2 emissions will decrease by 21% under the BAU scenario during 2021-2050. The total annual CO_2 emissions of the U.S. PVC resin manufacturing industry will drop from 3,925 kt CO_2/year in 2021 to 3,113 kt CO_2/year in 2050 under the BAU scenario.

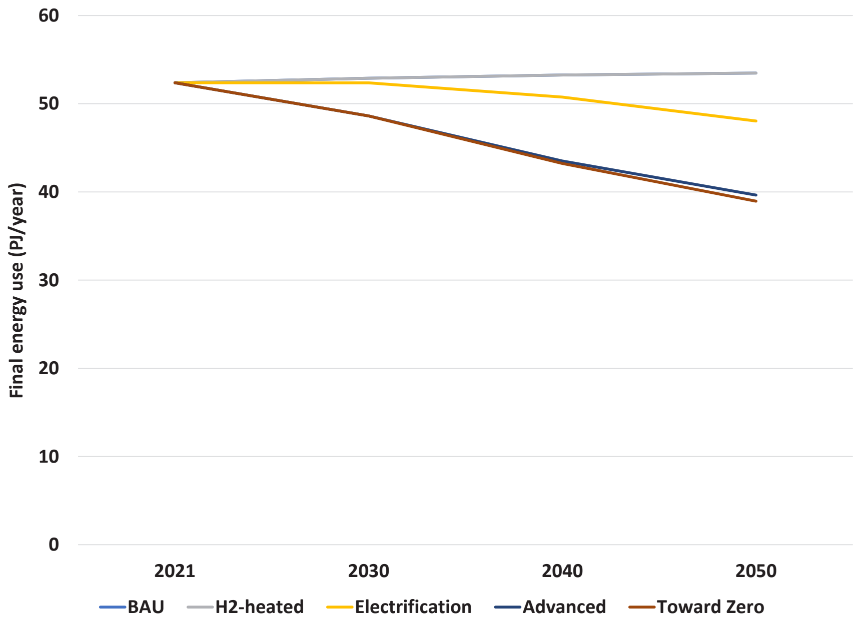


Figure 7: Final annual energy use in the U.S. PVC resin manufacturing industry under various decarbonization scenarios (Source: this study)

Although the Hydrogen (H2)-heated scenario will result in a slight increase in the total final energy use of the PVC industry during 2021-2050 (Figure 7), the CO_2 emissions of the U.S. PVC resin manufacturing industry will be decreased by 48% by 2050 under the H2-heated scenario. This is because a portion of the fossil fuel will be replaced by clean hydrogen, and the electricity CO_2 emissions factor in 2050 is around one-fourth of 2021 (See Table A.1). The total annual CO_2 emissions of the U.S. PVC resin manufacturing industry will drop from 3,925 kt CO_2/year in 2021 to 2,047 kt CO_2/year in 2050 under the H2-heated scenario.

Our analysis clearly shows that the electrification of boilers and furnaces can play a considerable role in the decarbonization of the U.S. PVC resin manufacturing industry. In the electrification scenario, although the total final energy use will reduce by only 8% during 2021-2050 (Figure 7), the application of electrified boilers and furnaces will reduce the annual CO_2 emission by about 57% by 2050 (Figure 8). The total annual CO_2 emissions of the U.S. PVC resin manufacturing industry will drop from 3,925 kt CO_2/year in 2021 to 1,686 kt CO_2/year in 2050 under the electrification scenario.

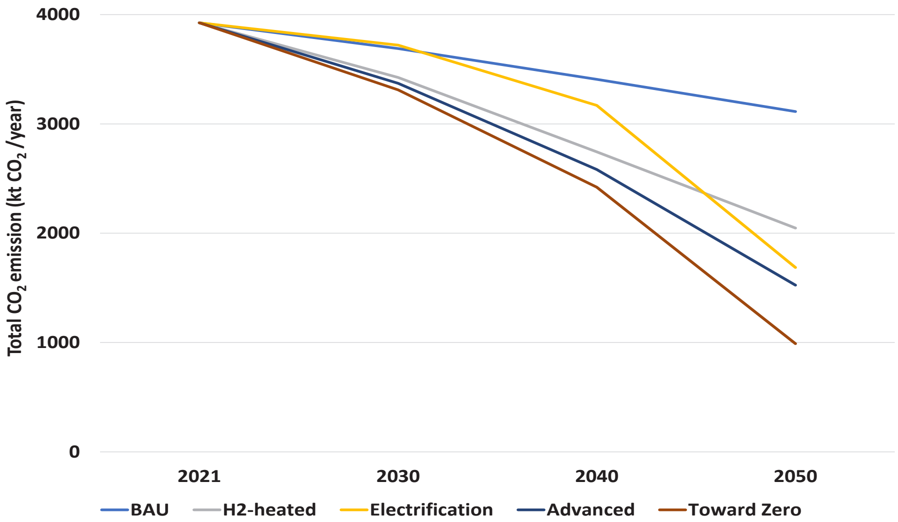


Figure 8: Total annual CO_2 emission in the U.S. PVC resin manufacturing industry under various decarbonization scenarios, 2021-2050 (Source: this study)

It should be noted that while electric furnaces for the PVC resin manufacturing industry are still emerging technologies, electric boilers are fully commercial technologies and are available off-the-shelf. The main challenge to electrification is the relatively lower price of natural gas in the U.S. compared to electricity prices. As the price of renewable energy production drops even further over time and the price of fossil fuels (e.g., natural gas) increases both because of market forces (such as the events in 2021 and 2022) or because of the introduction of some type of carbon price in the U.S. in coming years, the electrification technologies can become cost-competitive compared to the conventional combustion technologies.

The Advanced scenario assumes slight deployment of fuel switching to clean hydrogen (low adoption rate in 2050), the application of electrification for the cracking furnace (low adoption rate in 2050) and boilers (high adoption rate in 2050), a limited amount of biofuel in the fuel mix and a more aggressive contribution of the energy efficiency measures and technologies. The total final energy use will drop by around 24% by 2050 under this scenario compared to the base year (Figure 7). The total annual CO_2 emissions of the U.S. PVC resin manufacturing industry will drop from 3,325 kt CO_2/year in 2021 to 1,525 kt CO_2/year in 2050 under the Advanced scenario. For more detailed information on the adoption rate of decarbonization options under each scenario, please see Appendix 1.

The Toward Zero Emission scenario has the largest reduction in the annual final energy use and CO_2 emissions in the U.S. PVC resin manufacturing industry as it includes an aggressive contribution of energy efficiency measures, higher deployment of hydrogen-heated furnaces, and higher adoption of electrification technologies and a slightly higher amount of biofuel in the fuel mix. Under our Toward Zero Emissions scenario, the total CO_2 emissions from the U.S. PVC resin manufacturing industry will decrease to about 990 kt CO_2/year in 2050, a 75% reduction compared to the 2021 level (Figure 8). This is while PVC resin production in the U.S. is assumed to increase by 20% during the same period. It should be noted that if we assume 100% CO_2-free electricity in 2050 (instead of 75% that is used), the total CO_2 emissions from the U.S. PVC resin manufacturing industry will decrease to near zero in 2050 (See Appendixx 2.1).

Figure 9 illustrates the contribution of each decarbonization option to the annual CO_2 emissions reductions in the Advanced scenario by 2050. Electrification of boilers makes the largest contribution to CO_2 emissions reduction, followed by energy efficiency and then clean hydrogen as a fuel for furnaces. Results of our analysis show that the contribution of biofuels will be minimal compared to the other decarbonization options.

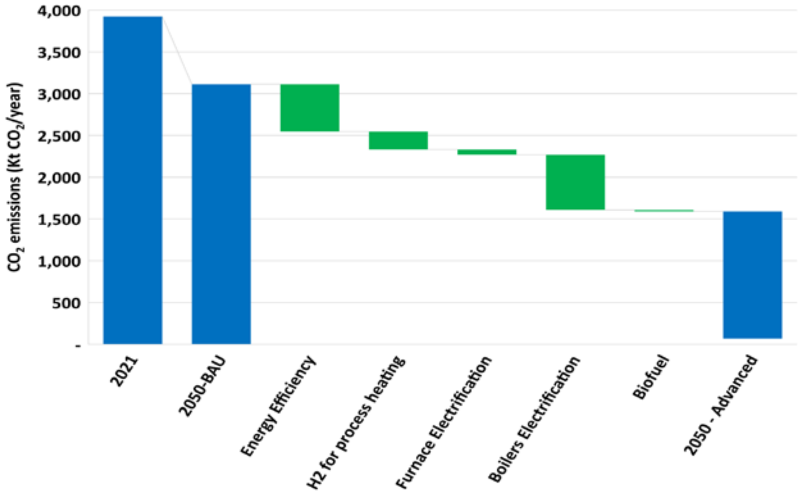


Figure 9: Impact of decarbonization options on annual CO_2 emissions under the Advanced scenario in the U.S. PVC resin manufacturing industry in 2050 (Source: this study)

Figure 10 shows the contribution of each decarbonization option to the CO_2 emissions reductions in the Toward Zero Emission scenario for the PVC resin manufacturing industry in the U.S. by 2050. In this scenario, the electrification of boilers makes the largest contribution to CO_2 emissions reduction, followed by energy efficiency and fuel switching of furnaces to clean hydrogen. Results of our analysis show that the contribution of the furnace electrification and sustainable biofuels will be lower than the other decarbonization options.

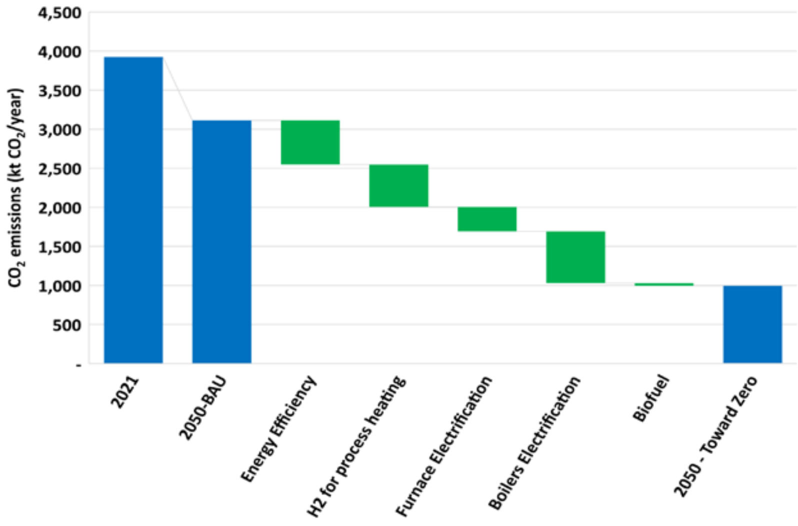


Figure 10: Impact of decarbonization options on annual CO_2 emissions under the Toward Zero Emission scenario in the U.S. PVC resin manufacturing industry in 2050 (Source: this study)

Each of these decarbonization options for the PVC resin manufacturing industry is discussed in more detail in the following sections. In addition to decarbonization options included in our modeling analysis, there are other technologies for reducing CO_2 emissions in the PVC resin manufacturing industry. For example, alternative feedstock and recycling can help to reduce CO_2 emissions from upstream and downstream of the PVC resin manufacturing industry but are outside of the scope of this analysis.

3.3. Decarbonization Technologies for the U.S. PVC Resin Manufacturing Industry

In this section, decarbonization technologies and their impact on the U.S. PVC resin manufacturing industry are discussed in more detail. These technologies are broken down into the following seven categories: 1) Energy efficiency, 2) Electrification of boilers, 3) Electrification of furnaces, 4) Furnace fuel switching to clean hydrogen, 5) Fuel switching to sustainable biofuels, 6) Decarbonization technologies for upstream of PVC resin manufacturing, and 7) Decarbonization technologies for upstream of the PVC resin manufacturing. These first five decarbonization technology categories are included in our scenario analysis, but the remaining two categories (6 and 7) are just qualitatively discussed in this report.

3.3.1. Energy efficiency

The application of energy efficiency measures and technologies reduces fuel and electricity use and thereby reduces their associated CO_2 emissions in PVC resin production processes. The technologies and measures are often well-known and cost-effective, providing immediate actions that can be taken in the near term to reduce the overall demand for energy and emissions in PVC production. There continues to be potential for further energy efficiency due to the development of new technologies and measures as well as further cost reductions of existing technologies and measures as well as systems optimization opportunities and emerging smart manufacturing technologies, advanced sensors and control systems, and industrial internet of things (IOT).

We have investigated the CO_2 emissions reduction potential that can be achieved through the application of commercialized and emerging energy efficiency technologies and measures in the U.S. PVC resin manufacturing industry. We have analyzed the gap between the energy intensity of the U.S. PVC resin manufacturing industry and that of best practices and practical minimum achievable energy intensity based on the values provided by the US DOE (2017). The impact of energy efficiency in CO_2 emissions reduction is smaller in BAU, Electrification, and Hydrogen-heated scenarios compared to that in the Advanced and the Toward Zero emission scenarios because we assumed lower energy intensity reduction rates in those three scenarios.

Results of our analysis show that the application of the best available energy efficiency technologies will result in the annual CO_2 emission reduction of 558 kt CO_2/year in 2050 under the Advanced and Toward Zero Emission scenarios. Some of the practical energy efficiency technologies and measures for the PVC resin manufacturing industry are energy efficiency in boiler and steam systems (US DOE 2022a, Hasanbeigi et al. 2014); energy efficiency in motor-driven systems such as pumps, fans, compressors, and machine drives (US DOE 2022b, McKane and Hasanbeigi 2010); energy efficiency in furnaces and process heating systems (US DOE 2022c); the use of promoters in EDC cracking; increases in the cracking conversion; heat recovery from the furnace combustion gases; heat recovery from the process gas of the cracker furnace; recovery of heat to the hot oil system in the oxychlorination reactor; in the case of high-temperature chlorination, use of the low-level heat of reaction to vaporize/distill the EDC; use of mechanical vapor recompression (MVR) systems to recover and reuse energy normally lost through evaporation; and heat recovery from the off-gas from incinerators and oxidizers (UNIDO 2016, UNDIO, 2018, Semeijn 2021, EECA 2019).

3.3.2. Electrification of boilers

Our modeling results show that the electrification of boilers has the greatest share of decarbonization potential in the U.S. PVC resin manufacturing industry. In the Advanced and Toward Zero Emission scenarios, electrification of boilers will reduce the annual CO_2 emission by around 662 kt CO_2/year in 2050 compared to the BAU scenario. In addition, the electrification of furnaces will result in a CO_2 emission reduction of 63 kt CO_2/year and 316 kt CO_2/year for the Advanced and Toward Zero Emission scenarios, respectively. Electrification could result in larger CO_2 emissions reduction if we assume 100% CO_2-free electricity in 2050 (instead of 75% that is used) (See Appendix 2.1).

Combustion boilers using fossil fuels to generate steam which provides heating for processes, are dominant in the global PVC industry. Water-tube boilers and fire-tube boilers are the most common types of combustion boilers deployed in the industry sector. Electric boilers, which are a mature technology, have a small market share for heat and steam generation in the U.S. industry. Given the high efficiency of electric boilers (98%-99% efficiency), they can have a large contribution to decarbonizing the PVC industry.

Electric boilers use electricity to heat water and generate steam. A thermostat is used to control the flow of electric current and the in-turn heating. The most common types of electric boilers are electric resistance boilers and electrode boilers. In electric resistance boilers, an electric-powered resistive element transfers heat to the water, raising its temperature to the desired level. In electrode boilers, the electric current passes directly through the water to boil the water. Electric resistance boilers typically possess lower thermal capacities (i.e., up to 5 MWe). On the contrary, electrode boilers have capacities generally ranging between 3 MWe and 70 MWe. Electric (resistance/electrode) boilers can generate superheated steam with temperatures of over 350°C and pressures of over 70 bars (Zuberi et al. 2021).

Compared to fossil fuel combustion boilers with an efficiency of 70-80%, electric boilers are also very efficient (i.e., 98-99% efficiency) with only minimal radiation losses from the exposed boiler surfaces. In addition, electric boilers possess many non-energy benefits, such as lower criteria air pollution (depending on the electricity grid fuel mix), lower permitting hurdles, and faster ramp-up times compared to combustion boilers (Rightor et al., 2020).

With today's technology, electric boilers (resistance/electrode) are capable of producing hot water and superheated steam at very high temperatures and pressures. Electrifying industrial boilers represent a great opportunity for GHG emissions reductions in the PVC industry, given the high share of steam systems energy use from total energy used in the PVC resin manufacturing industry, as shown earlier in this report. On average, the capital cost of an electric boiler is nearly 40 % less than that of an equivalent natural gas-fired boiler (Jadun et al. 2017). Low natural gas prices in the U.S. are the current fundamental challenge to the economics of electric boilers, although this may change as natural gas prices increase (as seen in 2021 and 2022) and renewable electricity prices continue to decrease as well the potential for introduction of some type of carbon price in the U.S. in coming years.

In our modeling analysis, we have assumed 75% CO_2-free electricity in 2050. However, the U.S. government has set a more ambitious goal to reach 100% CO_2-free electricity by 2035 (The White House 2021). Therefore, we have demonstrated what will happen if we assume a 100% CO_2-free electricity in 2050 in Appendix 2. If a 100% CO_2-free electricity in 2050 is realized, it will substantially help the deep decarbonization of the PVC industry in the U.S. when PVC plants electrify their boilers.

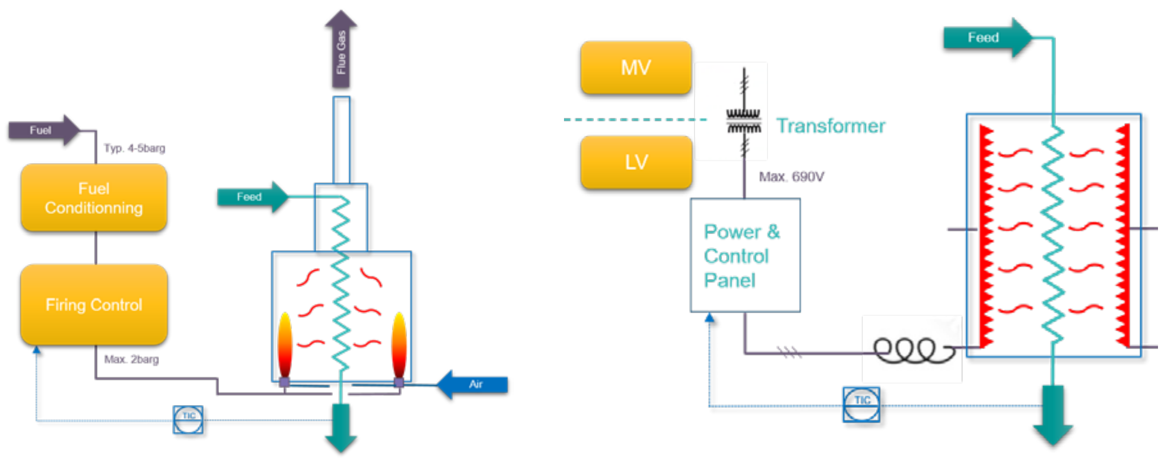
Also, it should be noted that, in practice, electrification projects will happen at the plant level. If a given PVC resin manufacturing plant in the U.S. electrifies its boilers and process heating demand today and purchases renewable electricity (e.g., through a power purchase agreement (PPA) or other mechanisms) to supply the electricity demand of the electrified process, the CO_2 emissions reductions from electrification can be achieved immediately. Therefore, PVC plants can electrify today and purchase renewable electricity and do not need to wait until the electricity grid is further decarbonized.

3.3.3. Electrification of cracking furnace

Our analysis shows that the electrification of cracking furnaces has a slight contributor to the decarbonization potential in the U.S. PVC resin manufacturing industry in our Toward Zero Emission scenario. The electrification of furnaces will result in an annual CO_2 emission reduction of 63 kt CO_2/year and 316 kt CO_2/year in 2050 in the Advanced and Toward Zero Emission scenarios, respectively.

The heat required for the continuous cracking reaction can be delivered by fuels, such as natural gas or hydrogen, but also through electric heating. Currently, all of the heat produced in the PVC industry is from fossil fuels. The electrification of cracking furnaces is a promising emerging decarbonization pathway for the PVC resin manufacturing industry, as indicated in other studies (Semeijn and Schure, 2020). Full electrification of the cracking furnace would lead to a significant decrease in CO_2 emissions when the electricity is generated from renewable sources. In this situation, the electric furnace eliminates all combustion-related emissions. There is currently no industrial-scale electric cracking furnace working in the PVC resin manufacturing industry. Therefore, further research, development, and demonstration (RD&D) projects are needed to advance this technology and its adoption in the PVC industry. The U.S. government, through the Department of Energy, should work with the PVC industry and use the great resources at the DOE national labs as well as other academic and private sector organizations for such RD&D projects.

Indirect resistance heating and dielectric heating are most suitable for the replacement of EDC cracking furnaces, as the temperature in the furnace is typically 500˚C. Especially indirect resistance heating is a suitable candidate for the PVC manufacturing industry (BZE 2018). An example of such indirect resistance heating technology is electrical tubular heaters. In this type of electric furnace technology, combustion burners are replaced by electrical resistors installed on the furnace walls to bring the required heat input to the process fluid flowing into the tubes. Figure 11 shows the tubular combustion heater (a) and electrical tubular heater (b).



(a) (b)

Figure 11: Combustion tubular heater (a) compared to an electrical tubular heater (b) for cracking furnaces (Source: Heurtey Petrochem Solutions 2022)

The electrical resistance furnace offers a uniform heat flux profile compared to traditional burners, hence reducing the heat flux peak and allowing for a decrease in the tube metal temperature and the fluid film temperature. The heat flux for the electrical heater is more linear. This solution can be specifically studied and put in place on the existing direct-fired heater during a revamp. This type of technology is still emerging and requires more development and demonstration across different industries, including the PVC resin manufacturing industry.

BASF, SABIC, and Linde have started construction of the world's first demonstration plant for large-scale electrically heated steam cracker furnaces. The demonstration plant will be fully integrated into one of the existing steam crackers at BASF's Verbund site in Ludwigshafen, Germany. The start-up of the demonstration plant is targeted for 2023 (BASF 2022). Shell and Dow have also been working on an experimental unit to electrically heat steam cracker furnaces at the Energy Transition Campus in Amsterdam, Netherlands. Electrified cracking furnaces operated using renewable electricity have the potential to reduce CO_2 emissions by 90% compared with conventional combustion crackers (Shell 2022).

3.3.4. Furnace fuel switching to clean hydrogen

Switching from fossil fuels to lower carbon-intensive fuels can help to significantly reduce CO_2 emissions associated with fuel use in the U.S. PVC resin manufacturing industry. We have investigated the extent to which PVC plants in the U.S. use fossil fuels and the potential for switching to clean hydrogen. We developed an H2-heated scenario where we made more ambitious assumptions on the share of clean hydrogen in the fuel mix in the U.S. PVC industry in 2050 (see Appendix 1 for the assumed share of H2 in the fuel mix under different scenarios). In the Advanced and Toward Zero Emissions scenarios, we have non-aggressive assumptions for the share of clean hydrogen in the fuel mix in 2050, which can be achieved even with current technologies or minimal change to current furnaces in PVC resin manufacturing plants.

Our results show that the CO_2 emission reduction potential from the partial use of clean hydrogen in the fuel mix will be around 213 kt CO_2/year and 540 kt CO_2/year under the Advanced and Toward Zero Emission scenarios in 2050, respectively.

Utilizing clean hydrogen as fuel instead of natural gas has the potential to directly avoid a large part of the emissions of any production plant using conventional natural gas burners (Semeijn and Schure 2020). Hydrogen can be produced from renewable energy sources, such as wind, solar power, hydropower, nuclear (clean hydrogen), from fossil fuels in combination with carbon capture and storage (CCS) (blue hydrogen), from fossil fuels without CCS (grey hydrogen), or as a by-product of other processes. In our analysis, we assumed the hydrogen that will be used in the PVC resin manufacturing industry would be clean hydrogen. The interchangeability of hydrogen versus natural gas can be judged using the Wobbe index. This index is a function of the higher calorific value and the specific gravity of the fuel gas, which is typically 45 MJ/m3 for hydrogen (McGlip and Livermore 2018). However, as the other gas characteristics are not similar, existing burners will most probably have to be modified (See below our discussion on hydrogen burners) (VNP 2018). The temperature, length, speed, and oxygen-to-fuel ratio of hydrogen flames are different from natural gas flames. Additionally, the heat radiative for hydrogen flames are less than that of natural gas flames.

The main challenge for the use of clean hydrogen as a low-carbon fuel in cracking furnaces is the availability of a large amount of clean hydrogen at a low price to make it economical for the industry to use it.

Another challenge is reducing the NOx emissions from hydrogen burners to adhere to the same regulations as natural gas since NOx emissions from hydrogen burners are significantly higher due to the increased flame temperature of combustion. Furthermore, when implementing hydrogen burners, the overall primary energy demand will increase as the hydrogen production process suffers from lower efficiencies. For example, the production of clean hydrogen from electricity only has an approximate efficiency of less than 70% (Semeijn and Schure 2020). Therefore, direct electrification of the cracking furnace would be a more energy-efficient alternative to the use of hydrogen. However, since the electrified cracking furnace for the PVC industry is not commercially available yet, the use of clean hydrogen in the fuel mix can be implemented with current technologies with minimal changes and therefore offers a decarbonization solution for the near term.

Hydrogen Burners

Due to the chemical differences between natural gas and hydrogen, their pure combustion differs in several ways, as shown below in Table 5. Because of the physical differences in the combustion of the two fuel sources, different design considerations must be accounted for in switching to hydrogen burners.

Table 5: Natural Gas and Hydrogen combustion characteristics (Ciniviz, 2022).

Combustion Characteristic	Natural Gas (Methane)	Hydrogen
Flame Temperature	1,915°C	2,207°C
Flame Speed	30-40 cm/sec	200-300 cm/sec
Lower Heating Value	50 MJ/kg	120 MJ/kg
Higher Heating Value	55.5 MJ/kg	141 MJ/kg
Combustible Range	5-15%	4-75%

Due to the eight times higher flame speed of hydrogen compared to methane, the design of hydrogen nozzles and injectors in burners is important to limit the speed and prevent backfire. Additionally, as discussed above, NO_x emissions can be higher at about 210-240 mg/ Nm3 without specific technological interventions. The higher flame temperature is also important to consider for compatibility with internal furnace equipment and materials such as combustion chambers, welds, and pipes.

To address these differences, however, current hydrogen burner designs and operation methods have been developed to solve these problems and continue to improve. To minimize NO_x development and lower the flame temperature, technology has been implanted to utilize internal or external gas recirculation of approximately 15-20% to achieve NO_x emissions reductions under current emissions limits for natural gas facility burners of 100 mg/ Nm3. The lower flame temperature that occurs with recirculation also may help to guarantee a higher lifetime of the equipment (E&M Combustion, 2021).

Hydrogen combusted along with 15-25% natural gas in burners has been shown to increase the calorific value of the mixture and achieve a stable flame with efficient combustion and may not require changes to the current burner and equipment. Additionally, natural gas helps to bring down the flame temperature and, thereby, the NO_x emissions. Combining natural gas with hydrogen does create more CO_2 than pure hydrogen-fueled burners, but the overall emissions are significantly decreased compared to natural gas as a fuel source. The mixing of hydrogen and natural gas can either be achieved through precise control of hydrogen and natural gas lines that combine at a manifold drum before entering the burner valve train, or the mixture can be introduced in the burner itself. This has been achieved, for example, by having the natural gas in the center of the burner to provide flame stability and hydrogen at other points (E&M Combustion, 2021). Several companies currently make hydrogen burners, and their use in industry is becoming more common. Table 6 below provides a list of some of the commercially available hydrogen burners and information on each.

Table 6. Sample of hydrogen burner commercial availability and additional details.

Company	Industry	Additional Details
E&M	Chemical	Double air register, reduced NOX emissions. Able to run on natural hydrogen gas and CO (E&M Combustion 2021)
SAACKE		20%-100% vol hydrogen (Saacke. 2021)
Selas	Refinery	Up to 100% hydrogen, low NOx (Selas Heat Technology 2021)
Toyota Motor Corporation	Steel	Allows slow combustion of hydrogen. The technology could replace 1,000 large-scale natural gas burners (Toyota 2018)
Tenova	Steel	100% hydrogen, Low NOx emissions, 78% efficiency (Zahra Awan 2021)
Linde Gas & Ovako	Steel	Oxyfuel (hydrogen and oxygen) fuel, no change to steel reheating, low NOx emissions (Ovako 2021)
FlammaTec	Glass	Oxyfuel (hydrogen and oxygen, up to 76% efficiency, low NOx (Flammatec 2022)

3.3.5. Fuel switching to sustainable biofuels

Sustainable biofuels can be used as an alternative fuel for cracking furnaces and steam production in the PVC industry. However, because of the limited availability of sustainable biofuels and other constraints, we made a conservative assumption for the use of sustainable biofuels as fuel in the U.S. PVC resin manufacturing industry (see Appendix 1). Based on this assumption, our analysis shows that the CO_2 emission reduction potential from partial use of sustainable biofuels in the fuel mix will be around 16 kt CO_2/year and 32 kt CO_2/year under the Advance and Toward Zero Emission scenarios in 2050, respectively.

Biomass is converted to energy through various processes, including:

- Direct combustion (burning) to produce heat;
- Thermochemical conversion to produce solid, gaseous, and liquid fuels;
- Chemical conversion to produce liquid fuels;
- Biological conversion to produce liquid and gaseous fuels.

Direct combustion is the most common method for converting biomass to useful energy. All sustainable biomass can be burned directly for industrial process heat and for generating electricity in steam turbines.

Thermochemical conversion of biomass includes pyrolysis and gasification used to produce syngas (CO and H_2). Both are thermal decomposition processes in which biomass feedstock materials are heated in closed, pressurized vessels called gasifiers at high temperatures. They mainly differ in the process temperatures and amount of oxygen present during the conversion process. The pyrolysis is conducted in the absence of oxygen at temperatures significantly lower than that of gasification.

A chemical conversion process known as transesterification is used for converting vegetable oils, animal fats, and greases in either the presence of an acidic or alkali electrolyte in excess methanol or ethanol into fatty acid methyl esters (FAME), which is the technical name for biodiesel.

Biological conversion uses anaerobic digestion or fermentation to convert sustainable biomass into ethanol and anaerobic digestion to produce renewable natural gas. Renewable natural gas, also called biogas or biomethane, is produced in anaerobic digesters at sewage treatment plants and dairy and livestock operations. It also forms in and may be captured from solid waste landfills. Properly treated renewable natural gas has the same uses as fossil fuel natural gas with the added benefit of combusting the otherwise potentially vented methane gas that has a much higher greenhouse gas warming potential (GWP) than CO_2.

Sustainable biomass could be used, potentially in a biogas form, to provide the heat supply for cracking furnaces. This would reduce net production emissions since the CO_2 released in combustion would be offset by the CO_2 absorbed during sustainable biomass growth (carbon neutral).

Steam in a PVC resin manufacturing plant is typically generated by natural gas-fired boilers. An alternative is a bio-combined heat and power (bio-CHP) plant, which directly combusts sustainable biomass. These systems can accept a wider range of sustainable biomass types and combust biomass in a stoker of a fluidized bed boiler to produce high-pressure steam, which is then passed through a steam turbine generator to produce additional electricity. However, they are more polluting than gasification systems, as the syngas in gasification systems is cleaned of contaminants (U.S. EPA 2007).

Syngas, also known as synthetic gas, is a gas derived from the thermochemical conversion of biomass through pyrolysis or gasification, often comprised primarily of carbon monoxide (CO) and hydrogen (H2) as well as some methane (CH4) – up to around 85% of the mix on average. Syngas is the primary output of gasification and is used primarily to generate energy. It is also often used interchangeably with the term "biogas," especially if the feedstock is organic and not fossil-fuel based. As an alternative, biogas and syngas could be used as fuel for steam production in the PVC resin manufacturing industry (PG&E 2018).

3.3.6. Decarbonization technologies for upstream PVC resin manufacturing

The replacement of petroleum-based feedstock with bio-based feedstock is nominated by many sources as an important decarbonization option for the petrochemical industry. Ethylene is one of the main raw materials in the production of PVC. Upstream of the PVC resin manufacturing industry can be decarbonized by the replacement of ethylene from naphtha with bio-ethylene from bio-ethanol. This opens the opportunity to avoid considerable amounts of CO_2 emissions, provided that the bio-ethylene production process and the origin of the biomass are sustainable (Fiorentino et al. 2018).

Bioethylene can be produced from bio-ethanol, which can be obtained by a series of processes from several types of sustainable biomass feedstock, such as sugars in corn, sugar beet, or lignocellulosic waste. The sugars are fermented, followed by distillation, to obtain bioethanol. Finally, bio-ethanol is dehydrogenated over an alumina or silica-alumina catalyst to produce bio-ethylene. Until now, the technology used to produce bio-ethanol is only demonstrated on a large scale in Brazil and the U.S., which are responsible for 83% of the world's production of bioethanol (Mohsenzadeh et al. 2017).

There is no consensus in the literature on the statement that bio-based PVC and other products produced from bio-ethylene will always result in CO_2 reduction. The carbon footprint is highly dependent on upstream factors, such as the type and sustainability of biomass and the local production logistics and infrastructure used (Dechema 2017).

During the production of 1 kg of bio-ethylene, 0.7 kg of CO_{2eq} is emitted. Therefore, the substitution of the fossil-based ethylene production process with bio-ethylene reduces CO_2 emissions by around 1.8 kg CO_{2eq}/kg ethylene. Currently, the production costs of bio-ethylene from bio-ethanol are substantially higher than the market price of fossil-based ethylene. More RD&D is needed to reduce the price of bioethylene. Additionally, future increases in the price of fossil fuels and possible carbon prices may make the production of bioethylene more cost competitive. Another consideration, which applies to all biomass decarbonization options, is whether or not there will be enough sustainable biomass available given all other applications and sectors that will be competing for access to the limited amount of sustainable biomass. Finally, the production of bioethylene also requires a substantial amount of energy. To ensure bioethylene has, in fact, low carbon intensity, this energy input should come from renewable sources.

There are other decarbonization technologies and measures that can be implemented in the upstream of PVC resin manufacturing such as carbon capture and storage (CCS) in the ethylene production and CHP units.

3.3.7. Decarbonization technologies for downstream PVC industry - recycling

Downstream of the PVC resin manufacturing industry can have a substantial contribution to the decarbonization of the PVC industry value chain primarily via the recycling of PVC products. The PVC recycling pathway is intimately linked to ideas of a more circular economy in which material loops are narrowed or closed through improved end-of-life processes and better product design.

More than 0.45 Mt of PVC is recycled in the U.S. and Canada every year. However, according to U.S. Environmental Protection Agency (EPA), around twice as much of vinyl products are landfilled today in the U.S. Most of the recycled vinyl comes from industrial or pre-consumer recycling. Post-consumer recycling of vinyl products has also increased in recent years, but the long operating life of PVC also contributes to the relatively low volumes of post-consumer recycling feedstocks available. Since 2014, there has been a 40% increase in post-consumer recycling. Approximately 66.2 thousand tonnes of post-consumer vinyl products are recycled annually in the U.S. and Canada. There are over 100 PVC recyclers in the U.S. and Canada. The Vinyl Institute hosts a recycling directory that identifies recyclers by state and province (Vinyl Institute 2022).

Recycling of PVC can be done by both mechanical and chemical processes, which are discussed below.

Improved mechanical recycling of PVC:
Mechanical recycling involves the shredding, cleaning, and remolding of PVC products from used PVC. The mechanical recycling potential of PVC – and plastics in general – is mostly determined by the degree of contamination of the plastic stream. The lower the contamination, the higher the purity of the stream consideration, and the higher the quality of the recycled PVC. Generally, the major part of PVC from pre-consumer waste has a high potential for high-quality recycling. Pre-consumer PVC waste streams are expected to have recycling rates of more than 70%. Those product groups where installation waste is most dominant generally have recycling rates lower than 70% as the PVC is contaminated and mixed with other waste. This is the case for the major part of building products. On the other hand, post-consumer PVC wastes have, on average, a lower recycling potential as it is generally more contaminated with other plastics types and consist of a mix of PVC with different compositions (Semeijn and Schure 2020, Bureauleiding 2019).

When high-quality recycled PVC is not feasible, downcycling can be done to still recycle the PVC material into lower-value products. PVC waste streams that are downcycled are typically mixed plastic waste fractions that consist of many different types of PVC with different compositions. Similar to high-quality recycling, the achievable mechanical recycling rate for lower-quality recycled PVC from pre-consumer waste depends on its origin.
Post-consumer PVC mechanical recycling potential for lower-quality recycling is limited to

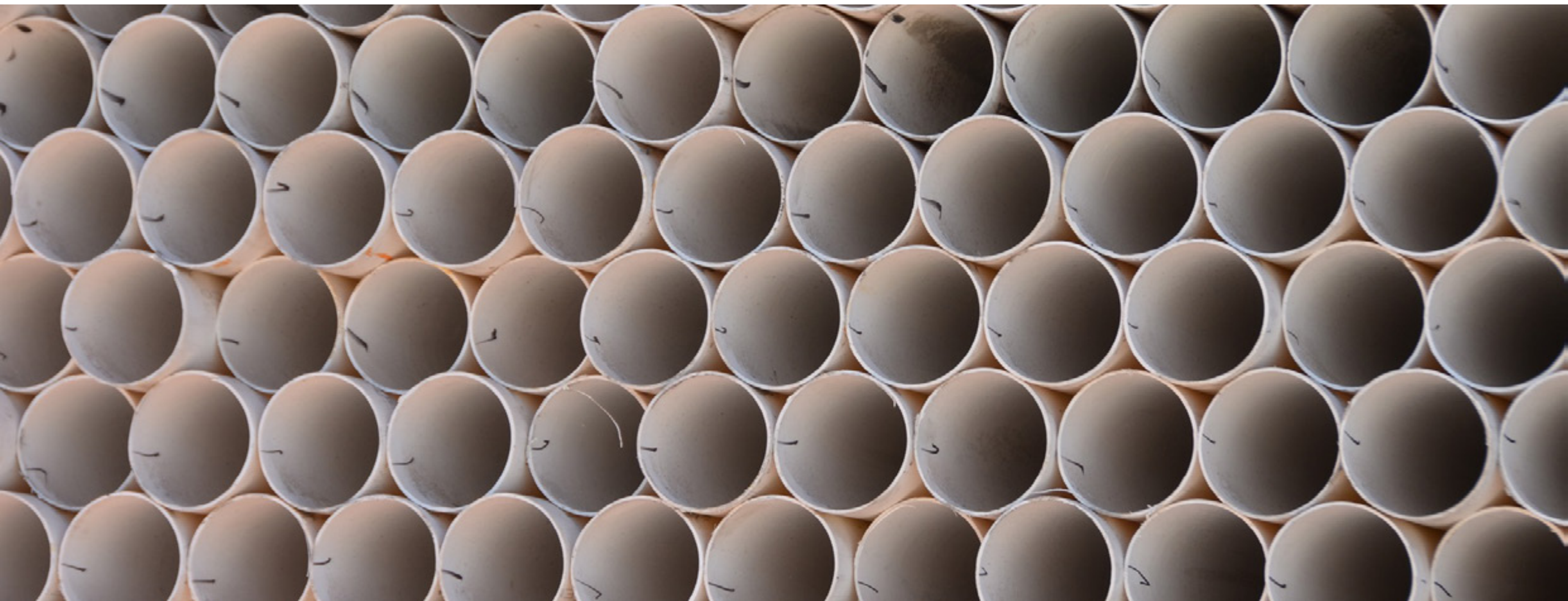
just a few PVC products in three waste groups. Downcycling cables is the major area of PVC recycling. Together with PVC cut-offs during installation, cable waste is used for the extrusion of piles and traffic cones. Mechanical recycling does not directly impact the PVC resin manufacturing production process. It only reduces the demand for virgin PVC, which in turn reduces the energy and carbon footprint of PVC products (Bureauleiding 2019).

Innovative non-conventional mechanical recycling of PVC:
PVC waste streams that are not suitable for conventional mechanical recycling, as described above, could potentially be treated using non-conventional mechanical recycling methods or chemical recycling. VinyLoop is an example of a non-conventional mechanical recycling technology (VinylPlus 2017). This process is categorized as a mechanical recycling method since it, in effect, does not break down the polymer, as is done with chemical recycling. VinyLoop is capable of accepting composite streams with up to 70% PVC content (Boulamanti & Moya 2017). PVC is selectively dissolved in a solvent, which makes it possible to simply filter out PVC material from a composite stream of different materials. The polymer is then recovered using precipitation and dried. The recycled PVC can then be used for applications such as shoe soles, hoses, and PVC sheets.

Chemical recycling of PVC:
Chemical recycling is seen as a complementary technology to mechanical recycling of PVC because the technologies in place are less sensitive to unsorted or contaminated waste products (PVC.org 2018). There are some streams of mixed PVC and plastics which are not suitable for high or low-quality mechanical recycling because the contamination of these streams is high. These waste streams are currently often incinerated. Chemical recycling could offer a solution to process these contaminated PVC streams for higher-valued use. Chemical recycling is, in essence, a way to recover carbon in PVC by producing useful chemical compounds from PVC waste that can again be used as feedstock in the industry (VinylPlus 2017). The two routes of chemical recycling are pyrolysis and gasification.

Conventional pyrolysis involves the anaerobic heating of the plastic stream to temperatures between 400–600 ^{0}C until it breaks down in pyrolysis oil, low-value fuels, and syngas. Integrated hydro pyrolysis is similar to conventional pyrolysis. However, in this case, the process is carried out in the presence of water. The operating temperatures are approximately 300–600 ^{0}C. This type of pyrolysis is often referred to as third-generation pyrolysis and is more suitable for heterogeneous input streams containing PVC (Semeijn 2021).

Gasification involves the heating of the material in the presence of oxygen and breaks down the stream to the smallest molecular building blocks: H2 and CO (syngas). Both low-temperature (800–1000 ^{0}C) and medium-temperature (900–1650 ^{0}C) gasification technologies are currently being developed. These options can be considered as two of the promising chemical recycling routes for PVC as well (Semeijn and Schure 2020).



4 Conclusions and Recommendations

The PVC resin manufacturing industry (excluding the feedstock chemical production) accounts for around 11% of total CO_2 emissions from the plastics and resins manufacturing sector in the U.S. With the world's growing population and increasing need for housing and other products that use PVC; the PVC demand will likely continue to increase in the coming years and decades. This means the energy use and GHG emissions of the PVC industry are likely to continue to increase globally if the current production methods are not substantially decarbonized.

Our analysis shows that there is a substantial potential for reducing CO_2 emissions in the U.S. PVC resin manufacturing industry. In fact, under our Toward Zero Emissions scenario, the total CO_2 emissions from the U.S. PVC resin manufacturing industry will decrease to about 990 kt CO_2/year in 2050, a 75% reduction compared to the 2021 level. This is while PVC resin production in the U.S. is assumed to increase by 20% during the same period.

Electrification of boilers makes the largest contribution to CO_2 emissions reduction, followed by energy efficiency and use the hydrogen for process heating. The contribution of furnace electrification and sustainable biofuels for heating and thermal processes is projected to be smaller because of our conservative assumptions due to techno-economic reasons.

The CO_2 emissions reduction identified in this study under deep decarbonization scenarios cannot be achieved without substantial deployment of new policy mechanisms in the U.S. and serious actions by PVC companies and other stakeholders. Below we briefly explain some key recommendations and key actions that the industry, government, and other stakeholders can take to accelerate the decarbonization of the U.S. PVC resin manufacturing industry.

The U.S. Government can work with the PVC industry to accelerate the decarbonization of this sector. The Inflation Reduction Act signed into law by President Biden in August 2022 includes $369 billion to address climate change. The U.S. also has set a goal to reach 100% CO_2-free electricity by 2035, which will substantially help the deep decarbonization of the PVC industry. The first US DOE Energy Earthshot, launched June 7, 2021—Hydrogen Shot—seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1"). Another recent US DOE Energy Earthshots Initiative, the Industrial Heat Shot, seeks to develop cost-competitive solutions for industrial heat with at least 85% lower greenhouse gas emissions by 2035. These government-sponsored programs can substantially help the PVC industry in its deep decarbonization path.

In addition, the US government can incentivize decarbonization of the US PVC industry by including PVC in its green public procurement (aka Buy Clean) program. This way, the public procurement of lower-carbon PVC products will create a demand pull for the decarbonization of the PVC industry. In September 2022, the United States joined the Industrial Deep Decarbonization Initiative (IDDI) – which is an initiative of the Clean Energy Ministerial and is coordinated by the United Nations Industrial Development Organization (UNIDO) to decarbonize heavy industries through various programs, including green public procurement.

Some other specific recommendations for the government and industry are listed below.

1) **Support research, development, and demonstration of emerging technologies and new applications of existing technologies**
Government and industry can work together to support technology demonstration and deployment. Many of the technologies included in this report are commercially available and ready for deployment (e.g., energy efficiency technologies and electric boilers). In cases where an "off-the-shelf" solution is not possible, PVC companies can work with original equipment manufacturers to further develop and refine technologies that meet their specific process and application requirements. PVC companies should also initiate partnerships with academia, think tanks, and other stakeholders to develop and/or scale decarbonization technologies. In addition, PVC companies should develop business cases for decarbonization technologies by including both energy and non-energy benefits. Advancing the technology development of electric furnaces for the PVC industry should be of particular importance, as demonstrated in this analysis.

Governments can act by incentivizing the deployment of decarbonization technologies in the PVC resin manufacturing industry. They can also help make advancements by using the excellent capacity of the U.S. DOE's national labs. Moreover, they can provide tax credits or grants to financially incentivize decarbonization technologies pilots and demonstrations.

Utilities can partner with industry and government to support RD&D activities for electrification technologies. They can also collaborate with industry and research institutes to evaluate the grid implication of electrification in their area of service and nationality. Suppliers of decarbonization technologies can collaborate with industry, academia, national labs, think tanks, service and engineering firms, and other stakeholders to scale their technologies.

2) Financially incentivize electrification and decarbonization
It is anticipated that renewable electricity prices will continue to decline and may decline faster than predicted, as has been the case in the past decade. This would make electrification technologies more competitive with conventional fossil fuel-based technologies. In addition, natural gas and other fossil fuel prices may increase more than projected (as was seen in 2021 and 2022), especially if a carbon pricing policy is introduced that includes the PVC resin manufacturing industry and the price of carbon increases up to 2050.

It should be noted that the energy cost is only a small portion of the total manufacturing cost in the PVC resin manufacturing industry. A small or even moderate increase in energy cost per unit of the product resulting from electrification will have a minimal impact on the price of the final PVC products. Therefore, it will have minimal impact on the price that final consumers will pay for the product or products made from those materials.

Governments and manufacturers may be able to reduce costs, especially for pilot or demonstration projects, by accessing public financial, technical, or program support. Governments may also implement their policies and programs aimed at reducing costs associated with decarbonization technologies adoption. Such policies could include tax incentives, reduced permitting costs, rate-based utility infrastructure upgrade costs, etc.

Grants for switching to electrified and other decarbonization technologies would reduce PVC manufacturers' upfront costs, incentivizing changes. Grants could be made for pilot projects to encourage early adoption and demonstrate success. The way utility rates are structured can also incentivize electrification. Electricity rates vary across states, so individualized approaches appropriate to each location would be needed.

Where possible, PVC companies can join the voluntary or mandatory carbon markets in the US to 1) generate and sell carbon credits from their decarbonization efforts thereby making a stronger financial case for their decarbonization projects projects, 2) buy carbon credits either to compensate for emissions that a company has not been able to eliminate yet or to neutralize residual emissions that cannot be further reduced due to prohibitive costs or technological limitations in order to get to net-zero emissions. The voluntary carbon market is gaining momentum in the US and globally and PVC companies should look into joining such carbon markets where posisble.

Finally, financiers require additional information about decarbonization technologies and their benefits. Those that could provide financing for decarbonization technologies may not be aware of PVC manufacturing decarbonization's full benefits. A better understanding of PVC decarbonization technologies' capabilities and the need for additional investment and support can improve policy and investment decisions.

3) Develop the workforce

Employees and contractors at PVC production facilities may require training on new technologies and their installation, operation, and maintenance. Governments can utilize their educational programs in technical schools, community colleges, and universities to provide training on current decarbonization technologies and ensure that the future workforce is ready to develop the next generation of technologies.

Governments should look across their agencies and offices, including education, higher education, energy, public utility commission, and economic development, to receive input on educational program development. Input from utilities, industrial companies, trade associations, teachers, and students will also be valuable to ensure training programs are meeting current and future needs. Those developing the workforce should engage with underserved communities and work together to develop relevant educational and training programs to ensure these communities can equitably participate in the clean energy economy.

4) Increase renewable electricity generation capacity

Additional renewable electricity generation resources are needed to maximize emissions reductions from industrial electrification. Ensuring that renewable electricity is used when electrifying PVC resin manufacturing through electric boilers, electric furnaces, and electric reactors will allow the emissions reduction potentials described in this report to be achieved. As the industrial, transportation, and building sectors all look to electrify and increase renewable electricity use, significant amounts of renewable electric power generation will need to be developed. The U.S. also has set a goal to reach 100% CO_2-free electricity by 2035, which will substantially help the deep decarbonization of industries such as steel and aluminum (The White House 2021).

The U.S. should support utility-scale renewable generation projects to increase capacity substantially and efficiently and work towards a zero-carbon electricity grid mix in 2035. In addition, ensuring that siting and permitting processes allow additional projects to be constructed will increase capacity.

Utilities will also need to ensure that renewable resources can connect to the transmission and distribution system. Interconnection of significant additional generation resources will require grid upgrades, as discussed further below. It is also critical to engage communities where renewable energy generation resources will be located and communities that may be impacted in other ways, such as preservation of and access to cultural resources.

The increased demand for renewable electricity across sectors will require not only additional supply but also an electric transmission and distribution (T&D) system that can adequately manage the increased energy volume. Electric utilities will need to examine the impact of increased electric demand on the system as a whole. New and upgraded equipment will be needed to meet the increasing demand.

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Appendices

Appendix 1. Modeling Assumptions

Table A.1 shows the weighted average electricity grid's CO_2 emission factor for the six U.S. states where PVC resin manufacturing plants are located (Texas, Louisiana, Kentucky, Illinois, New Jersey, and Mississippi).

Table A.1: Weighted average electricity grid's CO_2 emission factor for the six U.S. states where PVC resin manufacturing plants are located (Texas, Lousiana, Kentucky, Illinois, New Jersey, Mississippi)

	Unit	2021	2030	2040	2050
Emission factor for grid electricity	kg CO_2/MWh	415	321	215	110

Source: U.S. EPA 2021; Projections are our study.

The adoption rate of decarbonization technologies under each scenario is shown in Table A.2. The justification for the adoption rate assumption for each technology under each scenario is explained in the scenario definition section of the report.

Table A.2: An adoption rate of decarbonization options in the U.S. PVC resin manufacturing industry under each scenario (Source: this study)

	BAU scenario			Electrification scenario			H_2-heated scenario			Advanced scenario			Toward Zero Emission scenario		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
% reduction in energy intensity compared to the base year (2021)	5%	10%	15%	5%	10%	15%	5%	10%	15%	12%	24%	32%	12%	24%	32%
Share of hydrogen in cracking furnace's fuel mix	0%	0%	0%	0%	0%	0%	20%	50%	80%	5%	10%	20%	10%	20%	50%
Share of biomass in the total fuel mix	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	5%	0%	5%	10%
Share of cracking furnaces that are electrified	0%	0%	0%	5%	40%	80%	0%	0%	0%	0%	5%	10%	0%	20%	50%
Share of boilers that are electrified	0%	0%	0%	10%	40%	90%	0%	0%	0%	10%	40%	90%	10%	40%	90%

Appendix 2. Results of the Analysis with Alternative Grid Emisisons Factor Assumptions

In addition to the main analysis presented in the main body of the report, we developed two other side analysese:

1. An analysis assuming 100% clean electricity generation in 2050. This is because the U.S. government has set an ambitious goal to reach 100% CO_2-free electricity by 2035 (The White House 2021).

2. An analysis based on a conservative assumption of 57% clean electricity generation in 2050. This is based on current projection by Energy Information Administration (EIA)'s annual energy outlook (AEO). However, it should be noted that any "goals" that have not been implemented as actual laws and regulations are not included in the AEO. In addition, not all of the provisions of the recent Inflation Reduction Act (IRA) are currently incorporated into EIA's AEO. It is very likely that future version of AEO will increase the share of clean electricity generation in 2050 to much higher than current projection of 57%.

Appendix 2.1. Results of the analysis assuming 100% clean electricity generation in 2050

If we assume 100% clean electricity in 2050, the electrification of boilers and furnaces can play a more significant role in the decarbonization of the U.S. PVC resin manufacturing industry. In the electrification scenario, although the total final energy use will reduce by only 8% during 2021-2050, the application of electrified boilers and furnaces will reduce the annual CO_2 emission by about 90% by 2050 (Figure A.1). This is because we have assumed that the electricity that will be used in these electrified processes will be zero-carbon in 2050. The total annual CO_2 emissions of the U.S. PVC resin manufacturing industry will drop from 3,925 kt CO_2/year in 2021 to 412 kt CO_2/year in 2050 under the electrification scenario.

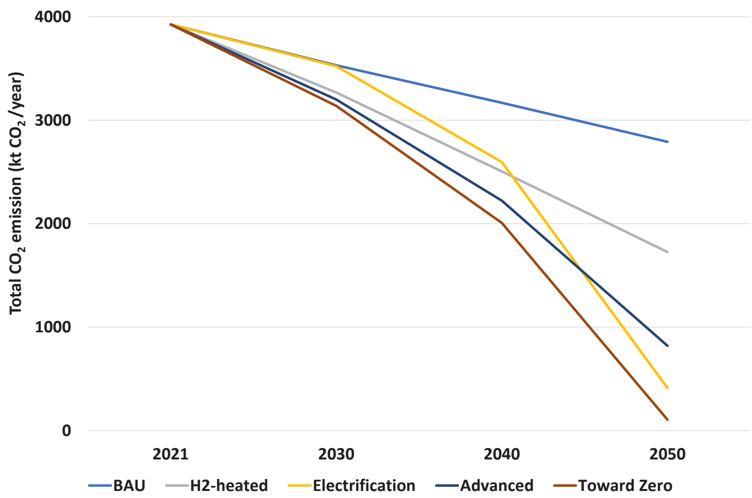

Figure A.1: Total annual CO_2 emission in the U.S. PVC resin manufacturing industry under various decarbonization scenarios assuming 100% clean electricity generation in 2050.

The Toward Zero Emission scenario under this analysis has the largest reduction in the annual final energy use and CO_2 emissions in the U.S. PVC resin manufacturing industry as it includes an aggressive contribution of energy efficiency measures, moderate deployment of hydrogen-heated furnaces, and higher adoption of electrification technologies and a slightly higher amount of biofuel in the fuel mix. Under our Toward Zero Emissions scenario, the total CO_2 emissions from the U.S. PVC resin manufacturing industry will decrease to about 0.1 Mt CO_2 per year in 2050, a 97% reduction compared to the 2021 level (Figure A.1). This is while PVC resin production in the U.S. is assumed to increase by 20% during the same period.

Figure A.2 shows the contribution of each decarbonization option to the CO_2 emissions reductions in the Toward Zero Emission scenario for the PVC resin manufacturing industry in the U.S by 2050. In this scenario, the electrification of boilers makes the largest contribution to CO_2 emissions reduction, followed by energy efficiency, electrification of furnaces, and furnace fuel switching to clean hydrogen with the almost same effects. Results of our analysis show that the contribution of the sustainable biofuels will be lower than the other decarbonization options.

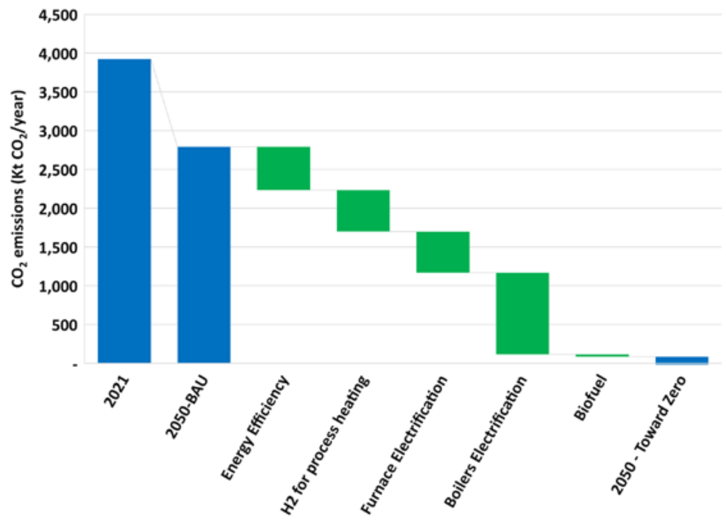

Figure A.2: Impact of decarbonization options on annual CO_2 emissions under the Toward Zero Emission scenario in the U.S. PVC resin manufacturing industry assuming **100% clean electricity** generation in 2050.

Appendix 2.2. Results of the analysis assuming 57% share of clean electricity generation in 2050

A conservative assumption of a 57% share of clean electricity generation in 2050 is another case study we analyzed. In this case, the fuel switching to clean hydrogen scenario will result in larger CO_2 emisisons than electrification scenario and will reduce the annual CO_2 emission by about 38% by 2050 (Figure A.3). The total annual CO_2 emissions of the U.S. PVC resin manufacturing industry will drop from 3,925 kt CO_2/year in 2021 to 2,428 kt CO_2/year in 2050 under the H_2-heated scenario.

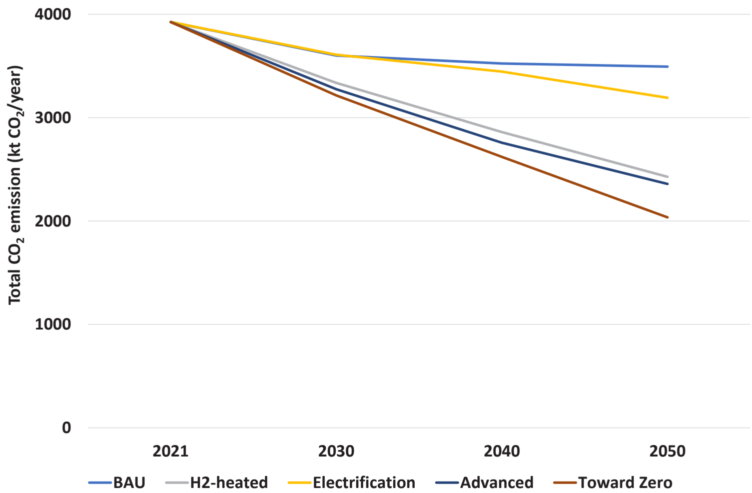

Figure A.3: Total annual CO_2 emission in the U.S. PVC resin manufacturing industry under various decarbonization scenarios assuming 57% clean electricity generation in 2050.

In the Toward Zero Emissions scenario, the annual CO_2 emissions in 2050 is higher than the previous case study where we assumed 100% CO_2-free electricity in 2050. According to this scenario, the U.S. PVC resin manufacturing industry's overall CO_2 emissions will be reduced to approximately 2,036 kt CO_2 annually by 2050, marking a 48% decline compared to levels in 2021 (see Figure A.3). Concurrently, PVC resin output in the U.S. is projected to grow by 20% during this timeframe.

Figure A.4 shows the contribution of each decarbonization option to the CO_2 emissions reductions in the Toward Zero Emission scenario for the PVC resin manufacturing industry in the U.S by 2050. In this scenario, the energy efficiency and the furnaces fuel swiching to clean hydrogen make the largest contribution to CO_2 emissions reduction, followed by electrification of boilers and furnaces. Electrification has a smaller contribution to the overall CO_2 emisisons reduction under this case study because of a more conservative assumption about the electricity CO_2 emissions factor.

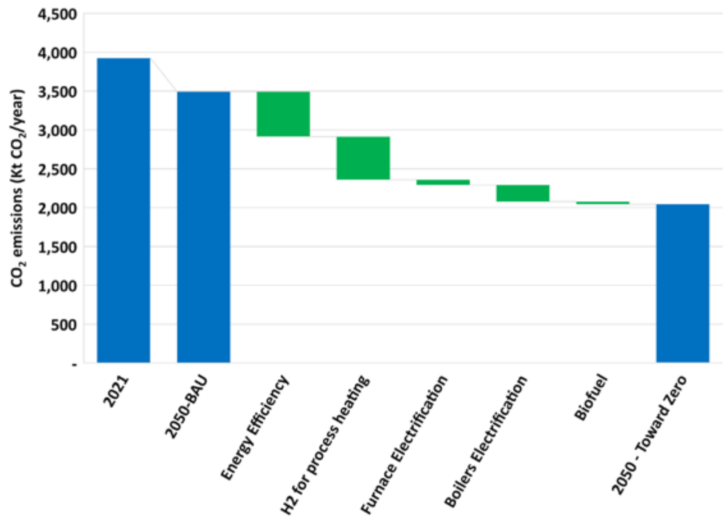

Figure A.4: Impact of decarbonization options on annual CO_2 emissions under the Toward Zero Emission scenario in the U.S. PVC resin manufacturing industry assuming 57% clean electricity generation in 2050.

Appendix 3. Description of the PVC Production Process

PVC is manufactured by polymerization of vinyl chloride monomer (VCM), which is produced by the thermal cracking of ethylene dichloride (EDC). Most of the ethylene used in the manufacturing of ethylene dichloride is produced by steam cracking of naphtha. The chlorine is derived from common salt (NaCl) by electrolysis. The manufacturing of the precursors EDC and VCM is described in the following section.

Production of EDC and VCM

EDC is the precursor of VCM. It is mainly used for VCM production, which is schematically illustrated in Figure A.5. Originally, VCM was produced by the gas-phase hydrochlorination of acetylene (ethyne) with hydrochloric acid (HCl) over a mercuric chloride-based catalyst. Due to the high cost of acetylene and the emergence of large steam crackers providing abundant ethylene, the acetylene route has been replaced by the chlorination of ethylene globally. Today, the original acetylene route is still widely used in Chinese production due to the availability of coal as a feedstock for acetylene production from calcium carbide (Plastics Europe 2015).

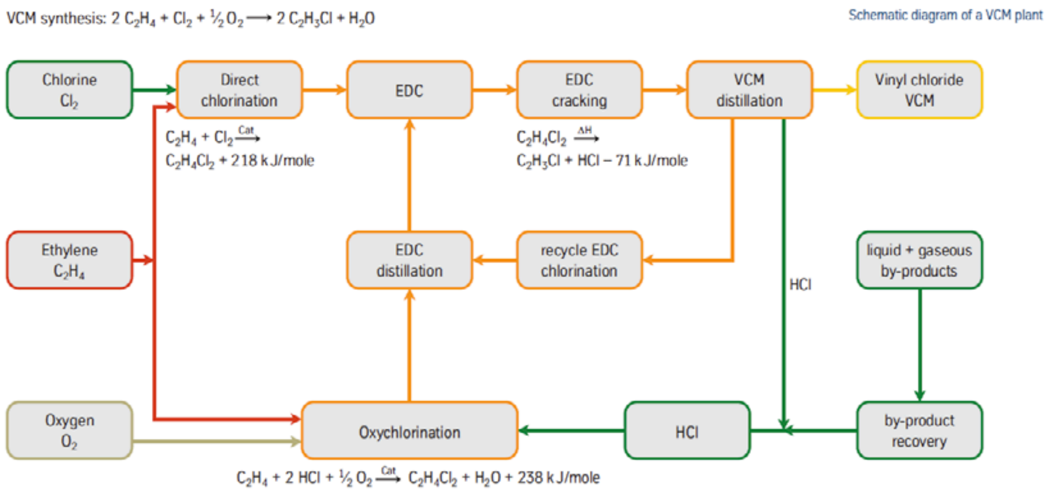

Figure A.5. Block flow diagram of VCM manufacturing process (Source: Thyssen Krupp Uhde GmbH 2012)

The chlorination of ethylene can either be carried out by using chlorine (direct chlorination) or by using hydrogen chloride and oxygen (oxychlorination). Thermal cracking of dry, pure EDC then produces VCM and HCl. When all the HCl generated in EDC cracking is re-used in an oxychlorination section, and when no EDC or HCl is imported or exported, then the VCM unit is called a 'balanced unit.' By using both direct chlorination and oxychlorination for EDC production, balanced units achieve a high level of chlorine utilization without producing HCl as a by-product. Assuming complete incorporation of chlorine input into EDC within a balanced unit, half of the produced EDC originates from each of the applied processes, direct chlorination and oxychlorination. Additionally, the heat gain from both highly exothermic chlorination processes may be used in the associated VCM production, optimizing the overall energy demand of the EDC/VCM/PVC production.

Direct chlorination of ethylene

The direct chlorination process of ethylene and chlorine is an exothermic reaction using the EDC product as the reaction medium. The operating temperatures are normally 50 - 120°C, and the applied pressure ranges from atmospheric to 5 bars. The reaction takes place in the liquid phase in the presence of a catalyst (usually Fe(III) chloride). A slight excess of chlorine or ethylene is preferred to ensure high ethylene conversion. The reaction product consists of >99% pure EDC. Less than 1% is made up of other chlorinated hydrocarbons, predominantly 1,1,2-trichloroethane and ethyl chloride. To reduce the formation of chlorinated by-products, an inhibitor can be added, typically oxygen.

Oxychlorination of ethylene

Compared to direct chlorination, the oxychlorination process yields less EDC but provides the HCl sink that realizes the balanced process. EDC and water are formed by the gas phase reaction of HCl, ethylene, and oxygen over a copper-salt catalyst at 220 – 250 °C at a pressure of 2 - 6 bar. Typically, fluidized bed reactors are used as reaction technology; fixed beds are also used in some plants. Regarding this highly exothermic reaction, temperature control is important to minimize the production of undesirable by-products. The recovered heat of the exothermic reaction is usually used to generate steam (Plastics Europe 2015).

EDC purification

EDC products, whether they originate from direct chlorination or oxychlorination, from VCM purification recycling, or from external sources, have to be purified since EDC cracking may be susceptible to inhibition and fouling by trace quantities of impurities. Purification may entail washing with water or caustic, azeotropic drying, heavy ends distillation, etc.

EDC cracking

The production of VCM from EDC is achieved by a cracking reaction followed by quenching of the process gas stream. When subjected to thermal cracking in heated furnaces at temperatures of approximately 500°C, purified EDC splits into VCM and HCl with conversion rates of 50 – 65%. The pyrolysis gases have to be cooled rapidly to reduce the formation of tars and heavy by-products. As mentioned above, the purity of the EDC feed has to be very high and greater than 99.5 weight percent. To reduce coke formation and fouling of the pyrolysis reactor. Figure A.6. shows the simplified flow diagram of the EDC cracking process (Thyssen Krupp Uhde GmbH 2012).

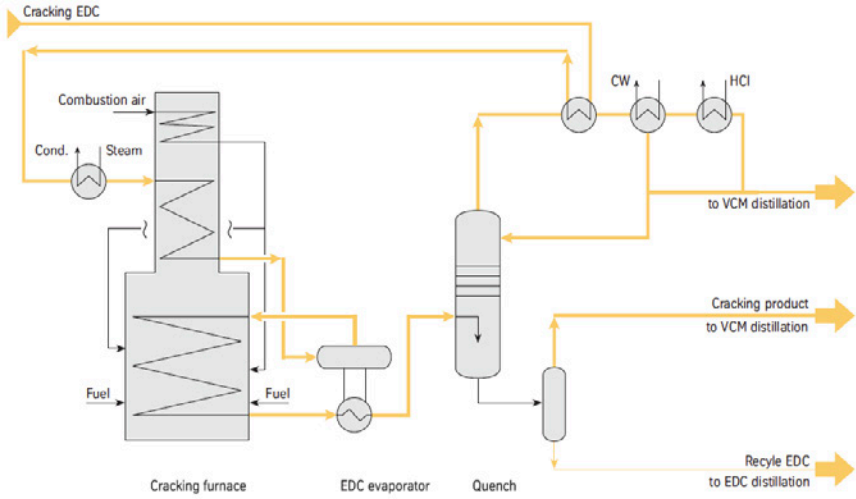

Figure A.6. Simplified flow diagram of the EDC cracking process (Source: Thyssen Krupp Uhde GmbH 2012)

VCM purification

After the cracking reaction, HCl and unconverted EDC are separated from VCM by two-stage distillation. Unconverted EDC is transferred back to EDC purification and recycled to the cracking furnaces. After an optional hydrogenation stage to remove any remaining traces of acetylene, distilled HCl is recycled as feedstock for oxychlorination. Most of the volatile by-products are removed via the HCl flow to oxychlorination. The liquid VCM product is transferred to storage after an optional step to remove the last traces of HCl (Plastics Europe 2015).

Polymerization

PVC is manufactured by polymerization of VCM. In the past, three main polymerization processes were used for the commercial production of PVC. Suspension polymerization (S-PVC) accounts for about 85% of global PVC production, emulsion polymerization (E-PVC) accounts for about 12% (Plastics Europe 2008A, B), and bulk polymerization accounts for about 3%.

Polymerization of PVC is an exothermic reaction. The pressure in the reactor is usually in the range of 0.4 – 1.2 MPa, and the reaction temperature is between 35 – 70°C. During the polymerization reaction, 85 – 97% of the VCM is converted into PVC. Residual VCM is removed by stripping the polymer suspension or latex. The unreacted monomer is recovered, liquefied, and returned to polymerization. For the production of emulsion PVC, inorganic peroxides are common. PVC suspension or latex can be concentrated before drying. For PVC suspension, this is usually achieved by dewatering via centrifugation. The PVC is then dried using a combination of temperature and airflow in dryers of various designs. E-PVC is usually spray-dried (Plastics Europe 2015).

The dried PVC powder is then stored in large silos and then transported to PVC product manufacturers either in small packages or large tankers.

Appendix 4. List of Acronyms

°C	Degree Celcius
°F	Degree Fahrenheit
BAT	Beat available technology
BAU	Business as Usual
BECCS	Biomass energy with carbon capture and sequestration
BTU	British thermal unit
CCS	Carbon capture and sequestration/storage
CCU	Carbon capture and utilization
CH_4	Methane
CHP	Combined heat and power
CO	Carbon monoxide
CO	Carbon oxide
CO_2eq	Carbon dioxide equivalent
EDC	Ethylene dichloride
EJ	Exa Joule
EPD	Environmental Product Declaration
E-PVC	Emulsion polymerization PVC
EU	European Union
FAME	Fatty acid methyl esters
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Giga Joule
GWh	Giga Watt-hour
H_2	Hydrogen
H_2O	Water
HC	Hydrocarbon
HCl	Hydrochloric acid
hr	Hour
IEA	International energy agency
kg	Kilogram
kton	Kilo ton
kWh	Kilo Watt-hour
m^3	Cubic meter
MJ	Mega Joule
MMBTU	Million British thermal unit
MVR	Mechanical vapor recompression
NaCl	Sodium chloride
NO_x	Nitrous oxides
PJ	Peta Joule
PVC	Polyvinyl chloride
SOA	State-of-the-art
SO_x	Sulfur oxides
S-PVC	Suspension polymerization PVC
TVR	Thermal vapor recompression
USD	United State dollar
VCM	Vinyl chloride monomer
yr	Year
µm	Micrometre