Blue and green hydrogen production, distribution, and supply for the Glass industry and the potential impact of hydrogen fuel blending in glass furnaces

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Figure 1

Description of Grey, Blue, and Green Hydrogen color classifications

Not Low Carbon	**Grey Hydrogen**	• Produced from a non-renewable hydrocarbon source • No carbon capture • Examples: Natural gas reforming; gasification
Low Carbon	**Blue Hydrogen**	• Produced from carbon sources with CO_2 capture • Carbon capture can be retrofit into existing facilities • Examples: Natural gas reforming with carbon capture; hydrogen from waste gas
Low Carbon	**Green Hydrogen**	• Produced from a renewable energy source (e.g., solar, wind, hydro) • Examples: Electrolysis with renewable energy

The global movement towards decarbonization spans across all industries, including Glass manufacturing. The current carbon reduction goals that have been set by global manufacturers require strong technical innovation and logistical development before they can be realistically achieved. The path forward for decarbonization in the Glass industry is not clear at this moment in time and there are several low carbon options being explored and developed to generate the high amount of carbon-free power required for glass melting and production. Green electricity and hydrogen have been widely discussed as potential options to help reduce and eventually eliminate the reliance on fossil fuel combustion. Both green hydrogen and electricity have various methods for production that create different levels of carbon emissions and it will take several years until the supply of either is commercially available to allow glass production to become decarbonized.

Air Products has made significant investments in blue and green hydrogen and ammonia production. Currently, there are three major projects in the Middle East, Canada and the United States in various stages of completion. Some aspects of these projects including production, distribution, and supply methods will be discussed. In addition, results using hydrogen as a fuel to replace natural gas combustion with existing oxy-fuel burner technology will be presented. These results will address some of the industry's concerns about the potential impact on combustion efficiency and heat transfer from the hydrogen-blended flames to the glass and furnace refractory

Blue and Green Hydrogen for the Glass Industry

Hydrogen is expected to play a key role in decarbonizing industry. According to the Kearney Energy Transition Institute report from June 2020, "Hydrogen could partially address [greenhouse gas emissions] as a fuel substitute in sectors responsible for more than 65% of global emissions" [1]. As industries make the switch to hydrogen as source of energy without associated carbon, it is important to note that the hydrogen will still have a carbon intensity which will vary depending on the means of its production. To make it easy to differentiate between the different hydrogen production methods/carbon intensities, industry has adopted the practice of referring to hydrogen using various colors. The most commonly used colors are grey, blue, and green. Grey hydrogen is produced using a non-renewable hydrocarbon source with all carbon emitted to the atmosphere in the form of carbon dioxide. Blue hydrogen is also made from a hydrocarbon source; however, up to 95+% of the carbon dioxide created in the hydrogen production step is captured and sequestered or utilized, resulting in a low carbon intensity hydrogen. Green hydrogen is produced from a renewable energy source (e.g., solar, wind, hydro), typically via water electrolysis, and so could have a carbon intensity close to zero. **Figure 1** highlights these various color schemes that describe the carbon intensity of hydrogen production.

To make the most of hydrogen as a means of decarbonization, it will be necessary for production to shift from grey to blue or green. The good news is that transition has already started. Air Products has recently announced world scale blue and green hydrogen projects to support the energy transition. The Alberta, Canada Net-Zero Hydrogen Energy complex is an example of blue hydrogen production. At this facility, natural gas will be used to make hydrogen via autothermal reforming. 95% of the carbon dioxide produced in this process will be captured and sequestered. A portion of the hydrogen produced will be used to make power for the facility and for export. Hydrogen will be delivered to customers either via pipeline or liquid hydrogen supply. The NEOM Green Hydrogen project [2] is an example of hydrogen production via water electrolysis using renewable energy (wind and solar). This plant will be located in Saudi Arabia, where renewable resources are plentiful. The hydrogen will be converted to ammonia to be shipped to other regions of the world where it will be converted back into hydrogen for decarbonizing the transportation sector and other industries.

The Glass manufacturing industry will require various amounts of hydrogen fuel and oxygen depending on the type of glass being produced. Typical hydrogen and oxygen supply quantities based on assumed furnace size are given in **Table 1**.

Table 1

Typical H_2 and O_2 supply quantities by glass type and assumed furnace size

Float Glass (650TPD Glass production)	
	• H_2: 490,000 SCFH (28 MTPD) – 11.8 MMSCFD (excluding tin bath)
	• O_2: 267,000 SCFH (241 MTPD) – 6.4 MMSCFD
Container Glass (400 TPD Glass production)	
	• H_2: 232,000 SCFH (13 MTPD) – 5.6 MMSCFD
	• O_2: 131,000 SCFH (118 MTPD) – 3.1 MMSCFD
Fiber Glass (240 TPD Glass production)	
	• H_2: 111,000 SCFH (6 MTPD) – 2.7 MMSCFD
	• O_2: 63,000 SCFH (57 MTPD) – 1.5 MMSCFD

Assumptions: 5% excess O_2 by vol; lower heating value of H_2 used; 96% O_2 purity for float glass & 93% O_2 purity for fiber and container glass

Highly packaged steam methane reforming (SMR) with carbon capture or water electrolysis plants are good options for the blue and green H_2 supply size ranges needed for all types of glass production, respectively. A typical business model for industrial gas suppliers is to own and operate the storage and reforming systems, so that the customer receives their hydrogen via a pipeline connection. The smallest size of an on-site generation process will typically use a packaged unit, designed as a standard product, that allows for rapid installation.

The glass industry's efforts towards decarbonization are currently much more active in Europe where natural gas prices are high. Also, the European Union Emissions Trading System (EU ETS) has developed a carbon market 'cap and trade' system [3] that essentially taxes industrial carbon emitters and such laws have been developed and enforced by the governments of many European counties. The EU ETS has created an economic driver that is accelerating the decarbonization process throughout Europe. In the U.S., there is currently slower adoption of serious decarbonization planning by most glass manufacturers, as there is no strong legislative incentive or carbon trading system in place to help to provide economical incentive to invest in these new decarbonization technologies. Nevertheless, many glass manufacturers are interested in decarbonization and the potential use of hydrogen to replace natural gas, especially as they consider future economic and regulatory changes that may take place during their long (up to 15 year) furnace campaigns. Several Glass manufacturers have also conducted hydrogen-blending trials recently. For example, NSG Pilkington conducted a H_2-blended trial in a float glass furnace and reported acceptable melting performance with no negative impact on glass quality or heat transfer within the furnace at 15% H_2 blended with natural gas [4].

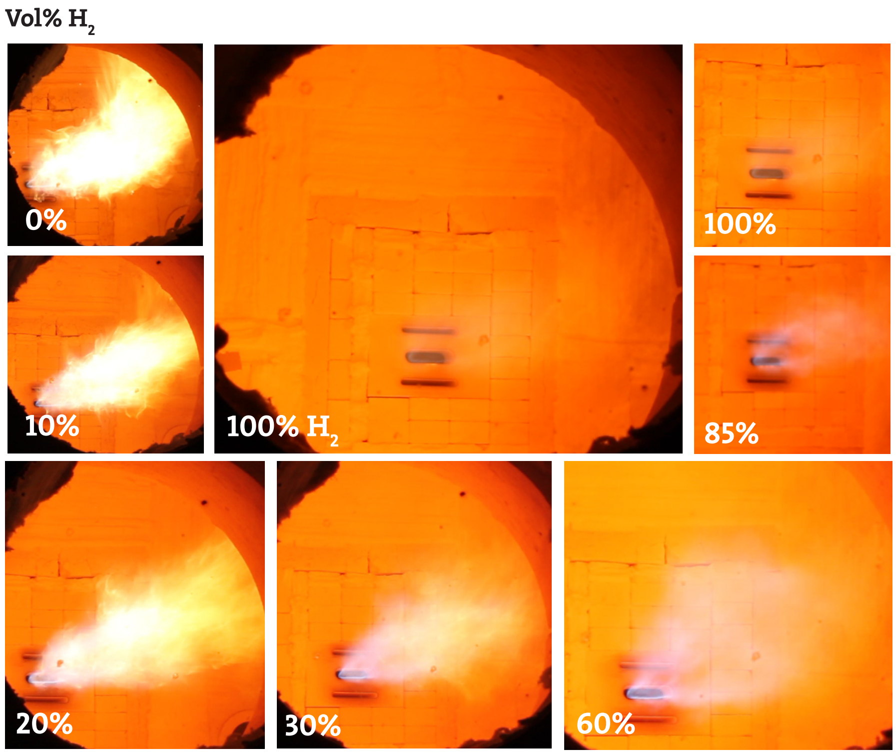
The Potential Impact on Hydrogen Fuel Blending in Glass Furnaces

The Glass industry has expressed some concerns with replacing natural gas with hydrogen fuel. These concerns revolve around the impact of H_2-blended fuels on their existing furnace infrastructure, combustion performance, and other effects on glass quality and furnace lifetime. Some specific concerns also include:

- A high concentration H_2 flame tends to be shorter and less luminous as compared to natural gas which may create localized higher breast wall temperatures and less heat transfer onto glass surface
- Higher potential NOx emissions due to the higher flame temperature of H_2-blended flames
- Potential negative impact of H_2 blending on overall heat profile inside furnace
- Burner and skid adaptability for H_2 blending and safety with H_2 gas handling

Figure 2

Combustion images of various H_2 blends using the HR_x burner. Blends included 0% H_2 up to 100% H_2 by volume with natural gas

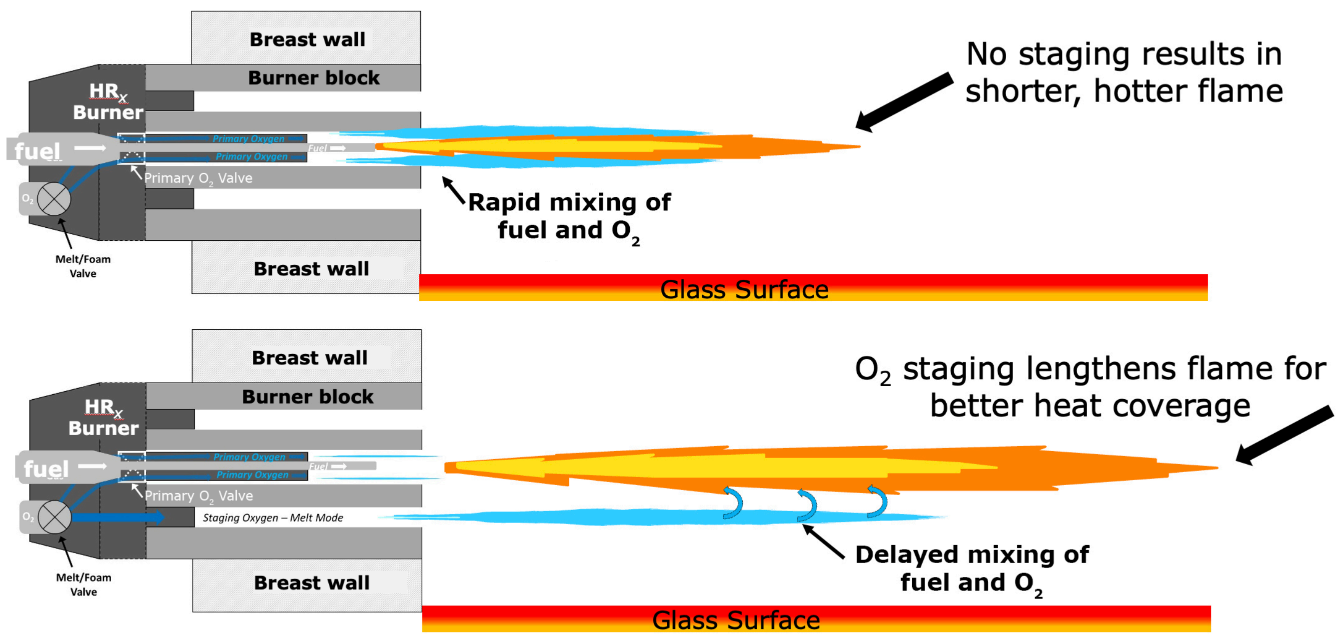


Air Products has conducted extensive lab testing using the Cleanfire® HR_x™ burner in response to these concerns and the Glass industry's general interest in carbon reduction. Various blends of H_2 with natural gas fuel were tested and flame properties such as length, luminosity, and NOx emissions were investigated. In addition to lab testing, Air Products is also currently participating in H_2 blending trials with glass manufacturers. The results of the trials are pending and will be available upon completion of the trials. The H_2 blending lab testing was focused on a 30% H_2/70% NG blend (by volume) as this seems to be the most practical blend that may be used commercially in the short term because existing natural gas pipelines can be employed to transfer this blend to glass manufacturing facilities. Higher H_2 blends (50-100% H_2) will be more important later when additional blue and green H_2 supply is available. **Figure 2** shows the impact of blending H_2 fuel with natural gas at concentrations of 0-100% by volume on the flame luminosity and length.

Figure 2 shows that the flame luminosity decreases with increasing hydrogen concentration. At 100% hydrogen, the flame is essentially invisible. In addition to the luminosity change, the flame length also tends to decrease with increasing hydrogen concentration. This is partially because the hydrogen-oxygen combustion reaction kinetics are much faster than natural gas-oxygen kinetics and therefore the bulk of the reaction takes place closer to where the fuel and oxygen streams mix as the gases exit the pre-combustor of the burner block. This can be controlled however with the use of oxygen staging, which delays fuel and oxygen mixing by splitting those

Figure 3

Oxygen staging allows for control of properties including flame length. The top image shows no oxygen staging where rapid mixing of fuel and oxygen results in a shorter flame with concentrated heat release near the breast wall. The bottom image shows that oxygen staging delays mixing between fuel and oxygen resulting in a longer, more luminous flame.



gas streams within the burner and burner block. With oxygen staging, the fuel and oxygen jets mix farther away from the breast wall, extending out into the furnace where the combustion reaction will occur. **Figure 3** depicts the oxygen staging process. The top part of the image shows no oxygen staging where rapid mixing of fuel and oxygen results in a shorter flame with concentrated heat release near the breast wall. The bottom part of the image shows that oxygen staging delays mixing between fuel and oxygen resulting in a longer, more luminous flame. It is important to note that the HR_x burner can distribute up to 95% of the staging oxygen to its staging ports. This very high level of oxygen staging provides a wide range of control of the flame properties compared to other oxy-fuel burners used in the glass industry.

Another factor that can cause the shortened flame length with H_2-blended fuels as compared to natural gas fuel is the design of the fuel nozzle. Hydrogen has approximately 1/3 the heating value by volume as compared to natural gas, so nearly 3 times higher volume flow of H_2 fuel is required to maintain the same heating rate as natural gas. The resulting higher fuel velocities of the H_2-blended fuel will accelerate the fuel and oxygen mixing process which will result in faster combustion and a shorter flame. The fuel velocities of a high concentration H_2 flame can easily reach the upper limit of the design fuel velocity for a burner that was designed specifically for natural gas. However, the fuel velocities can be controlled through small design changes of the fuel nozzle to accommodate the higher volume flow to keep velocities at a reasonable level. Our test results have shown that at H_2 blends less than 50%, the HR_x burner maintains good performance and does not require any design changes. However, as a result of observations made during these tests, minor fuel nozzle design changes were implemented for operation with fuels having 50-100% H_2.

Flame spectral measurements were also carried out as part of the lab testing of the HR_x burner with H_2 blending. **Figure 4** shows emission spectra measured between 200-1000 nm with various H_2 blends (0, 10, 30, 60, 100%) using the HR_x burner without oxygen staging. The spectral measurements were taken through a furnace window that was located only 0.3 meter (11 inches) from the hot face of the burner block. The spectral measurements show that as H_2 concentration increases so does the near-IR spectral emission intensity. This result highlights the fact that the H_2-O_2 combustion reaction kinetics are faster than the natural gas-oxygen combustion kinetics and heat release near the burner block is increasing as the H_2-blended flame becomes shorter. There is also competition between the additional water vapor generated by the H_2-blended flames and the infrared radiation generated by burning soot that is created by natural gas during combustion that is contributing to the increase in infrared emission intensity.

Figure 5 shows additional emission spectral measurements of the hydroxy (OH) radical measured at 310 nm. The OH radical provides an indication of progression and reactivity of the combustion reaction. The measurements were taken using 30% H_2/70% NG fuel blend at two locations, 11" (0.3m) and 48" (1.2m) from the hot face of the burner block (as shown on the x-axis of the graph). The measurements were taken at two burner conditions, both with and without oxygen staging. The radiation intensity corresponding to the OH peak at 310nm, as shown on the y-axis, shows greater intensity in the 11" and 48" locations for the case with no oxygen staging (i.e., H_2 flame is shorter). When oxygen staging is employed however, the peak intensity drops by as much as 54% and 37% in the 11" and 48" windows, respectively. This means that the combustion reaction is shifting away from the breast wall and further

Figure 4

Flame emission spectra measure between 200-1000 nm with various H_2-NG blends (0, 10, 30, 60, 100 Vol%) using the HR_x burner without oxygen staging.

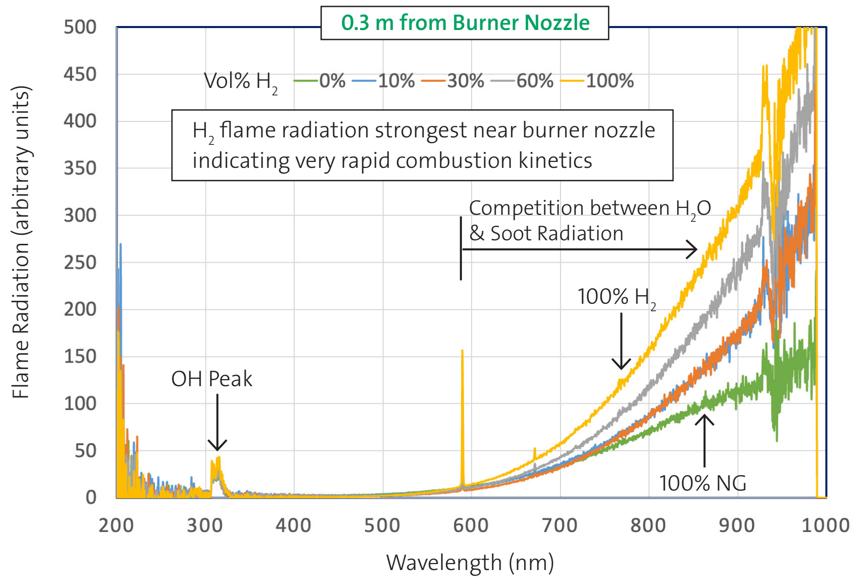
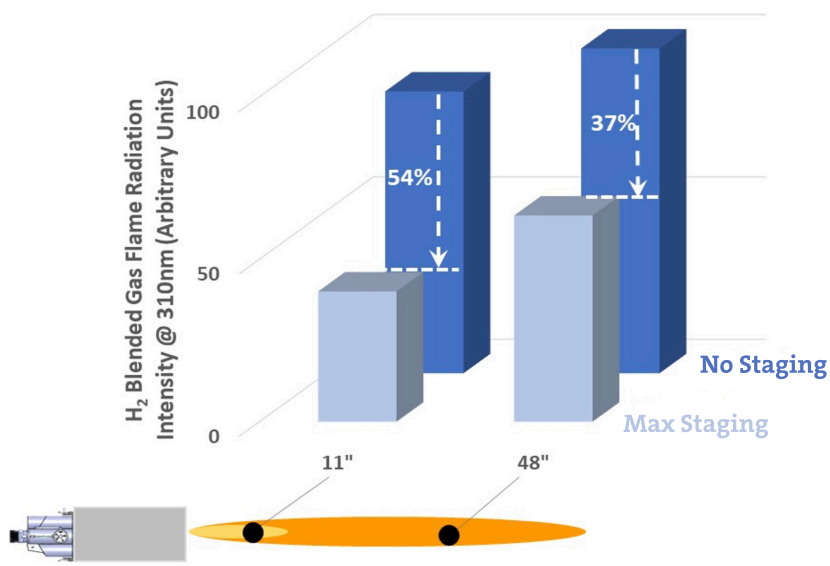


Figure 5

Spectral emission measurement of the Hydroxyl (OH) radical using the HR_x burner with 30% H_2/70% natural gas blends at two locations from the breast wall (11" and 48"). The case with oxygen staging shows that the intensity of the combustion reaction is shifted away from the breast wall and thus confirms that oxygen staging is still an effective tool at controlling flame properties with H_2-blended fuels.



downstream into the furnace. **Figure 6** shows an additional set of results using thermocouples embedded into the breast wall of the furnace that further corroborate this result. Four thermocouples were embedded ½" below the surface of refractory in each of the four corners of the burner block. When transitioning from a 100% NG fuel to a 30% H_2/70% NG blended fuel without oxygen staging, the temperature of the breast wall increased by approximately 19˚C. But when flame was optimized by using maximum oxygen staging under the same conditions, we measured a 36˚C decrease in the local breast wall temperatures in the vicinity of the flame. These results show that oxygen staging is still an effective tool to control flame properties such as flame length, even with H_2-blended fuels.

NOx emissions using H_2-blended fuels was also investigated. **Figure 7** shows that when transitioning from 100% natural gas fuel to 30% H_2/70% NG blended fuel, NOx emissions levels only increased by approximately 6% when using the HR_x burner without oxygen staging. But when oxygen staging was maximized, we measured a further decrease of NOx of approximately 12%, which is a net decrease of 6-7%. The reason that oxygen staging is effective at preventing NOx formation is because the delaying mixing of oxygen and fuel results in a lower initial flame temperature where most NOx is produced. This result again highlights the importance of using oxygen staging to control flame properties and NOx emissions, especially with H_2-blended fuels.

Figure 6

Four thermocouples embedded in furnace breast wall show an increase in wall temperatures by 19˚C when transitioning from 100% natural gas to 30% H_2/70% NG blend. But when oxygen staging is activated, a 36˚C decrease in wall temperature is observed.

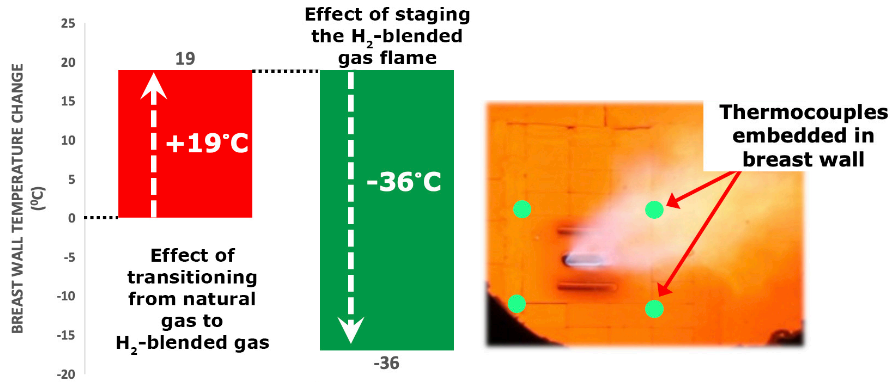
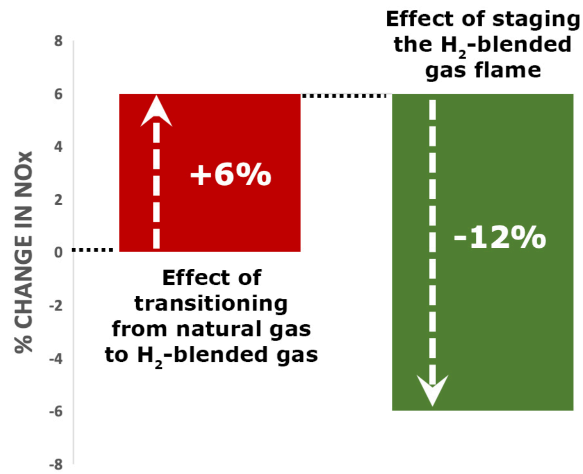


Figure 7

Percent change in NOx emissions levels. Only 6% increase when transitioning from 100% NG to 30% H_2/70% NG when using the HR_x burner without oxygen staging. But when oxygen staging was maximized, we measured a further decrease of NOx of approximately 12%.



In conclusion, the Air Products Glass Combustion R&D team has conducted extensive lab testing using the HR_x burner with various hydrogen and natural gas fuel blends. The results show the HR_x burner performs well with H_2-blended fuels and requires no change in design with H_2 blends as high as 50% and only minor changes with H_2 blends between 50-100%. Flame properties such as flame length and NOx emissions levels can be optimized by using the HR_x burner's oxygen staging feature which is effective even with H_2-blended fuels. This is an important result for glass manufacturers because the burners can remain the same, with only flow skid changes required to accommodate the H_2-blended fuel supply. Additionally, Air Products is establishing critical Blue and Green H_2 production hubs throughout the world to help our customers meet their carbon reduction goals.

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