Natural gas produces the fewest emissions of all hydrocarbons, and is considered the major transition fuel as renewable energy potentially becomes the world’s primary energy source. This has been accelerated by the signing of the UN Paris Climate Accord in 2015, which provides a framework and targets for the reduction of greenhouse gas (GHG) emissions for 195 countries.

Natural gas has been used for decades as an energy source, but in many countries its use has been limited by availability due to location. LNG technology was initiated in 1918 as a way to extract helium from natural gas for use in dirigibles. Commercial operations related to liquefying natural gas, at least in the US, did not truly take off until the mid-1940s. LNG technology, used to liquefy natural gas for more efficient transport, began its development in the 1950s, with the first ship transport of LNG being made in 1959 by the converted carrier, Methane Pioneer. This was followed in 1964 by the first new-build LNG carrier, Methane Princess, which delivered its cargo of just over 27,000 m³ to Canvey Island, UK. This was the genesis of the LNG marine shipping industry.

LNG storage plants were then planned and built at select port facilities to facilitate the importation of this valuable energy source. Stored in liquid form at -162°C and ambient pressure, it contains 1/600th the volume as gas. Once liquefied and transported, the LNG could then be regasified and added to the regional gas grid, sent directly to a power plant, or introduced at needed intervals to offset high energy demands to maintain steady supply.

Through the early 2000s large land-based LNG plants were constructed with LNG carrier access to port facilities based on long-term gas supply contracts. However, not all users had the luxury of having a port facility in proximity to demand locations.

David Waronoff and Arun Duggal, SOFEC, USA, consider the Tower Yoke Mooring system as a solution which can bring LNG storage and regasification technology closer to areas of LNG demand.
which is important for easy transfer and storage. These locations may also not have the necessary available acreage or infrastructure to build LNG storage and regasification facilities. In addition, there may be certain locations for which LNG would be a supplement to natural gas sources already available, being used to meet peak demand or to expand supply over time. In these cases, the market demanded new solutions that would allow quick development of the infrastructure to store and regasify LNG, or to be able to buy gas on the spot market when required. One of the solutions developed was the floating storage and regasification unit (FSRU).

In the mid 2000s, the Excelerate Gulf Gateway and Golar Spirit FSUs were commissioned. These were the world’s first FSUs with one jetty moored in protected shallow water, while the other was moored in unprotected deeper water using a single point mooring. The Gulf Gateway was a deepwater port solution, incorporating a submerged turret loading (STL\textsuperscript{TM}), and allowed for specially built FSUs to moor, offload regasified LNG, and sail away. As such, it fulfilled the needs of the region during high demand periods.

With the current demand for reduced emissions, and the increasing availability of LNG for new markets, a number of FSRU projects are in various stages of development, especially in countries focused on reducing emissions by replacing coal and oil with gas. For certain markets and new locations, it was obvious that an alternative to deepwater moorings needed to be developed. This new mooring solution would necessarily allow the FSRU vessel to be located closer to shore to minimise the offshore pipeline length, and have capability to moor a permanent FSRU to maintain a steady flow of gas to high demand end-users. In early applications, mooring dolphins with jetty protection were put in place when shallow water port infrastructure was not available. However, even if ports existed close to the required import demand, in many cases, the local residents and port authorities were reluctant to allow an FSRU to permanently moor for various reasons, including safety issues, quay availability and continual side-by-side offtake from very large gas carriers that can create more port congestion and increase potential risks. Thus, a robust shallow mooring system that can facilitate side-by-side offloading in the open seas provides an appealing alternative.

**Origin of the Tower Yoke Mooring system**

As mentioned, the Gulf Gateway FSRU was an offshore single point mooring (SPM). SPMs were originally conceived in the 1950s as a way to minimise the environmental loads from wind, waves and currents by allowing the moored vessel to freely rotate into a position of least resistance. Shell developed and patented the Catenary Anchor Leg Mooring (CALM) Buoy in 1959. The CALM Buoy was primarily used to transfer liquid hydrocarbons in a shallow water between onshore storage tanks and the offshore transport tanker. However, these shallow water mooring systems were only operational in approximately 2.5 m seastates, given the use of a flexible hose for fluid-transfer from the seabed, as well as a light catenary mooring system with relatively low capacity for station-keeping. This was of little concern as these tankers were moored temporarily only to load oil in order to bring it to market and vessels were not required to be permanently moored.

However, permanent moorings are needed for fields requiring floating production and storage systems where fluid flows continuously to or from the moored vessel. In 1962, Esso Libya installed a fixed tower with a rotating head to moor a dedicated storage tanker of approximately 100 000 bbl capacity. The limitation on this installation was the mooring hawser as it alone provided the elasticity needed to keep the vessel on station. Although intended to be a permanent storage facility, in rough seas the vessel would depart the mooring and production was suspended. The challenge was then identified to find a solution for a permanent shallow water mooring that provided the restoring force to allow a vessel to stay on location in more severe weather conditions. The SPM companies, of which SOFEC is one, responded by developing the Tower Yoke Mooring system.

In 1999, CNOOC contracted SOFEC Inc. to design and supply the mooring system for the FPSO Bohai Shi Ji to be installed in Bohai Bay, China. This SPM system is specifically designed for shallow water (20 m in this case) and includes a ‘soft yoke’ for mooring a vessel directly to a fixed tower as shown in Figure 2.

This Tower Yoke Mooring (TYM) system includes a large ballast tank filled with water to provide the necessary restoring force to minimise vessel offsets and loads. The two mooring link arms, with U-joints on either end to provide motions in all degrees of freedom, suspend the tank from a support structure mounted on the vessel. The yoke links the vessel to the turntable mounted atop the mooring tower via pitch and roll joints to allow the yoke to capture relative motions between the vessel and the tower. The turntable is fastened to the tower with a roller bearing to allow the vessel to freely weathervane about
the tower. Product, utilities, power and control signals are transferred from the tower across swivels located on the turntable and through hoses and umbilicals from the turntable to the vessel. Ample deck space is available on the tower for manifolding, pigging and auxiliary equipment as illustrated in Figure 3.

A major advantage of the TYM system is that there are no flexible risers from the seabed to the tower; the risers are hard piped from the seabed to the top of the jacket, while umbilicals are pulled through J-tubes. This ensures that the TYM system can be used in very shallow water in relatively harsh environments and not have to consider the limitation of a flexible riser system under those conditions. The flexibility in the flowlines are provided by the jumpers from the rotating side of the tower to the mooring support structure on the vessel.

SOFEC has subsequently supplied four other TYM systems and has recently been contracted to supply a ‘quick’ disconnectable TYM system that shall be installed offshore Mexico. This disconnectable TYM system will be the first of its kind and demonstrates the versatility of this concept which can be adapted for FSRU systems in cyclonic regions.

SOFEC’s fourth TYM system was developed for the world’s first tower-yoke-moored FSRU, which was delivered to Hoegh LNG in 2012. SOFEC’s experience with the previous systems played a big part in the decision to go forward with this first application for gas transfer. The vessel, **PGN FSRU Lampung**, is a 170 000 m³ very large gas carrier moored in 23 m of water. The system is installed 22 km from shore near Labuhan Maringgai, Indonesia. Gas transfers through a fully redundant swivel stack assembly and flexible pipe to a single 24 in. gas pipeline. Import gas is supplied by LNG carriers that moor side-by-side for offloading LNG to the FSRU. The system was classed by DNV GL.

The typical TYM system is designed for water depths up to 35 m and seastates up to 7 m significant wave height. This limitation can prove to be challenging in certain parts of the world. For instance, in the Gulf of Mexico where hurricanes are experienced multiple times in any given year, much higher seastates are not uncommon. To address this challenge, the disconnectable tower yoke system was developed. The system grants FSRUs the ability to sail away from an impending storm, taking with it all appurtenances related to mooring. Meanwhile, the jacket structure remains behind and, as it is designed to withstand a 100-year storm, it will be ready for the vessel to return once the storm has passed. This design development was based on the track record developed by SOFEC on both permanent TYM systems and disconnectable turret moored systems that have disconnected and reconnected more than 60 times over the past 12 years.

In addition to the standard FSRU, MODEC Inc., SOFEC’s parent company, has been developing a floating storage regasification, water and power solution (FSRWP™), which includes power generation using onboard FSRU technology to store and regasify the LNG, as well as electrical generators and desalination skids for producing potable water. For SPM systems, this requires the development of a high voltage swivel at approximately 133 kV and 1000 amps to be able to send power to shore. SOFEC is in the process of developing such an SPM for which the tower yoke mooring system is a natural choice in shallow water when no jetties are available as illustrated in Figure 4.

**Conclusion**

With 11 TYM systems now operating worldwide, this SPM technology has proven to be a reliable option for mooring a vessel when jetty space is not readily available and water depths are too shallow for catenary anchor legs with flexible risers. The use of this technology also allows one to select an optimum location with respect to proximity to end-users, local marine traffic, pipeline length, shore approach and port requirements.

The ever-increasing demand for natural gas in all parts of the world should see the application of the TYM system increase. The TYM system is a solution that can provide a means to allow importation of natural gas close to any coastal demand centre.