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De-risking E-Drive Retrofits at Aging LNG Plants: Lessons Learned from Feasibility Studies

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Abstract

A number of LNG plants across the globe that were built in the late 20th century are approaching the end of their design life. For most of these plants, feedstock is still available in sufficient quantities for continued LNG production (in some cases, at higher rates than current plant capacity or emissions permits will allow). Over the last two years, Siemens Energy has received several customer requests for feasibility studies to evaluate the conversion of main refrigeration compressors (MRCs) from mechanical drives to electric motor-driven trains. Most of these requests have originated from operators of legacy LNG plants that currently utilize steam turbines or older gas turbines as prime movers. This paper presents key insights from said studies and discusses important factors for stakeholders to consider when evaluating a brownfield electrification project. Drawing on available data, the paper provides a comparison of a complete compressor string replacement approach vs. a driver swap at an undisclosed LNG plant.

Introduction

In recent years, LNG operators have come under increased pressure to reduce the carbon footprint of their facilities. To achieve this, both greenfield and brownfield facilities are evaluating the inclusion of various sustainable technologies. While strategies involving carbon capture, utilization, and storage (CCUS) and the use of alternative fuels (i.e., hydrogen blending in gas turbines) will likely play an important role in the coming years, electrification remains the most robust approach to decarbonization. Electrification of drive systems not only has the potential to remove greenhouse gas (GHG) emissions (depending on the source of electricity), but also facilitates the use of current and potential future green energy sources.

Virtually all large-scale greenfield projects under development and some of those that have reached final investment decision (FID) within the last decade feature designs with MRCs driven by electric motors and variable speed drives (VSDs). Several brownfield projects which utilize gas or steam turbine-driven MRCs are also evaluating retrofit/upgrade projects that would see the installation of new electric motor drives (E-drives). In many of these cases, an external grid connection was not available at the time of the plant's construction. In others, the grid has or soon will see the incorporation of a low-emissions power source (i.e., nuclear, hydro, solar or wind with battery energy storage, etc.), which will open the possibility to reduce GHG emissions from the facility.

Often, the limiting factor of a brownfield electrification project is not CAPEX, but rather the downtime and loss of revenue associated with it. Conversion of a mechanically-driven MRC train is a complex undertaking that carries significant execution risks, particularly when it comes to testing and interconnection. Depending on the facility and the new driver being installed, there may also be a requirement to reinforce existing foundations. This is especially the case when steam turbines are being swapped out for electric motors, which are typically much heavier.

Siemens Energy has performed several feasibility studies that have looked at various E-drive retrofit/modernization strategies for LNG plants. The two most common approaches are:

- Direct swap of the steam or gas turbine with an electric motor, while maintaining some, or all, of the existing compressor's components. In certain cases, it may be possible to do a complete re-aero of the compressor internals and conversion of the gearset, including stationary and rotating parts, without changes to the casing, external process connections, and/or existing footprint. Using some internal stationary and rotor components, in combination with new rotating and/or static parts is also possible.

- Total replacement of the existing mechanically-driven MRCs with new electric motor-driven trains using the same footprint.

While both approaches are possible, they result in significant plant downtime and execution risk. As an alternative, Siemens Energy has proposed to install a new replacement packaged electric motor-driven compressor string in proximity to the existing strings (or in another designated location in the plant, depending on the layout congestion). In such cases, new cabling and associated piping can be built and routed to a convenient tie-off location for connection to existing upstream and downstream equipment – ideally when the plant is shut down for planned maintenance. This approach effectively de-risks project execution by eliminating several key activities from the critical path and enables a large portion of the work scope to occur while the plant is up and running.

E-Drives vs. Mechanical Drives

The use of E-drives opens new possibilities for controlling the liquefaction process, while at the same time making plant operation more efficient, reliable, and sustainable. E-drives offer numerous advantages over gas and steam turbines for liquefaction due in large part to the higher efficiency of electric motors (>95%). A single-shaft industrial gas turbine operating in an open-cycle configuration has an efficiency of around 25 - 30%. Single-shaft aeroderivative gas turbines in an open-cycle configuration can achieve efficiencies upwards of 38 – 42%. While steam turbines with reheat cycles can achieve slightly higher efficiencies, it typically comes at the expense of increased emissions, as steam is produced via gas-fired boilers.

As seen in Figure 1 below, over a wider speed range and load profile, an electric motor can deliver higher efficiencies compared to gas turbines.

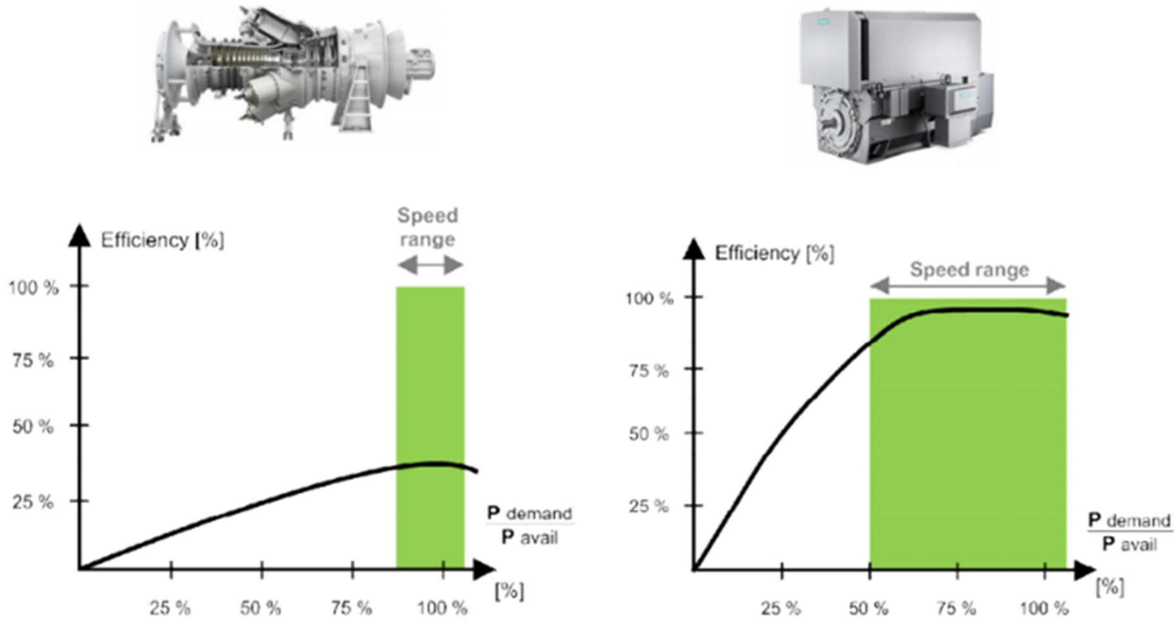

Figure 1 – Refrigerant Compressor Driver Efficiency

Table 1 below shows refrigerant compressor train efficiencies for a gas turbine and an electric motor-drive designs. As seen, an E-drive design with a power island onsite can provide as much as a 6% higher efficiency, resulting in a corresponding reduction in CO_2 emissions.

Table 1 – Aeroderivative Mechanical Drive vs. Electric Drive LNG Facility Efficiency

Drive Train Efficiency Contributor	Mechanical Drive Design	Electric Drive Design
Compressor	85%	85%
Gas Turbine	40 – 42%	N/A
Electric Motor	N/A	98%
Transformer	N/A	99%
Variable Frequency E0Drive (LCI Drive with Harmonic Filter)	N/A	98%
Transmission	N/A	98%

Drive Train Efficiency Contributor	Mechanical Drive Design	Electric Drive Design
Drive Train Efficiency (Grid Connection)	34 – 36%	80%
Power Island Electrical Efficiency	N/A	50%
Drive Train Efficiency (Power Island)	34 – 36%	40%

Electric motors also provide advantages over gas and steam turbines with respect to availability and maintenance. A typical gas turbine-driven LNG plant design has an availability of approximately 95%. After two years in operation, anywhere from 1-3 weeks is required for scheduled maintenance. Electric drives, on the other hand, can achieve 99% availability, thus decoupling the length of scheduled maintenance from the MRC driver to other equipment like replacing of molecular sieve. Furthermore, it is not uncommon for large motors to go as many as 5-6 years without scheduled maintenance.

Project Risk Profiling

A conceptual study is the first step in determining the feasibility of an E-drive conversion. These studies are critical for developing the project's overall risk profile and identifying an optimal approach/strategy given site-specific variables and operator objectives.

Before considering the drive train itself, the availability and capacity of the electric energy source must be evaluated. In the case of grid-connected plants, a grid study must be performed to analyze harmonics, power factor corrector, protection philosophy, safety concept, grounding, and optional filter design (depending on the type of drive), etc.

Unlike mechanically-driven trains, E-LNG plants are subject to harmonic distortion and voltage fluctuations produced by large motors and VFDs, which can lead to unnecessary plant trips. Understanding the effects of these harmonics on the stability and reliability of the plant's electro-mechanical system is critical to preventing downtime. This is a topic that is discussed in further detail in a separate 2023 Gastech Paper titled "*Optimizing E-drive Design: Applying Best Practices from Other Industries*".

Organizing a site survey to capture information such as layout, available space, and existing infrastructure (e.g., piping, connections, foundation), compressor details, etc. is also necessary prior to drive train design and foundation analysis. Furthermore, for a long-term OPEX comparison, a service concept for the new installed equipment needs to be defined, which includes, for example, the spare part concept and service intervals. Heat integration is another important area that must be evaluated, as waste heat is typically captured from the exhaust of the gas turbine.

Evaluating E-Drive Retrofit on a Real-world LNG Plant

In this section, we present the results of a brownfield electrification project conceptual study at an undisclosed liquefaction plant (grid-connected). The plant currently features multiple MRCs driven by mechanical drive turbines. The conceptual study evaluated two possible solutions:

- **Solution 1:** Replacement of the existing turbines with high-speed synchronous motors (i.e., direct driver swap) without replacing the compressor casings.

- **Solution 2:** Replacement of the existing compression strings with new motor-driven compressor configurations (i.e., total string replacement).

The new compressor strings for Solution 2 are fully tested prior to shipping and installed in a proximate location to the existing strings. The primary advantage of this approach is the elimination of scheduled downtime by performing a large portion of the construction and installation work scope while the plant is in operation. Any activities that must be performed with the existing trains shutdown should be scheduled during a planned outage.

Table 2 below provides a general comparison of the two solutions. A +/- correlates with a perceived advantage/disadvantage for each solution.

Table 2 - Comparison of Solution 1 vs. Solution 2

Solution 1 Direct Driver Swap		Solution 2 Total String Replacement		Unscheduled Shutdown
-	Major demolition scope required to accommodate motors	+	Compressor string 3 area is free and clear	Y
		-	Compressor string 1 & 2 area requires demolition of existing feed gas compressors	
-	Will require significant craneage to set the motors	+	Compressor skids can be set using self-propelled modular transporter direct from Material Offloading Facility	Y
		+	Potential for Debottlenecking Compressors	
-	Two separate Motors for HP MR and LP MR	+	One large motor for compressor string 3 HP&LP compressor skid	
-	Full Alignment and leveling of Motor	-	Alignment and leveling of Train 3 Motor and HP&LP MR Compressor Skid	Y
-	Full Testing Scope must be performed	+	All Compressor Skids will be fully tested prior to shipping	Y

-	Separate E-House for HP MR and LP MR	+	Compressor string 3 HP&LP MR Requires one motor and hence one less E-House	
-	Demolition of Feed Gas Compressor to accommodate compressor string 1&2 E-Houses	-	Additional land reclamation necessary to accommodate compressor string 1&2 E-Houses	
		-	More cable length due to distance from E-House to compressor string 1&2 Motors	
-	Terminate and test all cables from VFD to Motor during shutdown and only then energize the system	+	Fully energize system prior to shutdown	Y
		-	Installed capacity of the motors 10MW greater than Solution 1	
+	Only pipe demolished to facilitate potential reinforcement of the tabletop will require reinstallation or rerouting	-	Major reinforcement of the existing racks and associated foundations & Installation of new racks to accommodate new pipe	Y
		-	Substantial scope of tie-in work required	
		+	Tie-in can be performed during planned shutdown	
-	Reinforcement of tabletop (Extent Unknown)	+	Limited equipment foundation installation which can be carried out during facility operations	Y

As the table illustrates, there are pros and cons to both solutions. The extent of the negative or positive attributed to each solution is not representative of the scale of work required. For Solution 1, the major disadvantage is the shutdown time required to perform the motor swap (and all related activities). For Solution 2, it is the requirement to reroute the piping from the existing facility to the new compressor skids.

Constructability

This section compares each solution from a standpoint of constructability and reviews the activities that can be performed during operations and those that should be performed during shutdown.

Mechanical

The constructability challenges for the mechanical scope are limited. Solution 2 is developed with the intention of building a single lift module for each string, which does not require mechanical alignment onsite. For one of the existing strings, two modules containing the compressors and the motor are on a separate base. The full string is tested prior to shipping; however, it will require some alignment onsite. This can take place prior to the plant shutdown. Solution 1 requires motor alignment with the compressors on the existing foundation and full testing performed during the shutdown period.

Electrical

Both solutions involve the installation of new E-houses containing VFDs and an additional modular Gas-Insulated Substation. In the chosen locations, land reclamation is necessary to accommodate both solutions. Demolition in the existing plant is also necessary to set the E-house for multiple compression strings. In addition to setting the new electrical equipment, there is a substantial amount of interconnecting cable which must be laid in tray and trenched in accordance with the chosen routing. These activities can be carried out (for the most part) during operations and in parallel to the equipment setting activities. The sequence of construction activities that can be performed during operations in areas where no demolition is required, and areas of newly allocated land, is as follows:

- Perform site preparation of the area
- Install foundations
- Set VFD E-houses and/or modular GIS (note: E-houses and GIS will be fully tested as much as practical prior to shipping)

The following is the expected construction sequence for cable installation:

- Install new racks and reinforce existing racks
- Identify space in existing trenches or excavate for new trenches or trench boxes
- Install cable trays
- Pull all cable, coil, and protect for final termination
- Perform continuity tests on field run cable
- Connect cables from GIS to E-houses and test
- Terminate all field run cables to the E-houses

For areas that require demolition of essential plant, the steps detailed above should be performed for setting the E-house after completion of the demolition activities. In addition, the following activities must be carried out:

- Terminate cables from GIS to E-houses and test
- Install the new motors for Solution 1 or the new compressor skids for Solution 2
- Terminate the field run cables
- Perform point-to-point test
- Energize the GIS and perform system function test

Piping
The scope of Solution 1 piping construction work is dependent on the amount of pipe required for operations of the new configuration. It is determined using the amount of pipe that will need to be demolished or rerouted for modifications to the existing tabletops required to accommodate the motors.

The scope of installation of piping for Solution 2 is extensive, however; the majority of this work could be carried out during normal plant operations. The installation of additional piping requires a combination of optimizing space in the existing racks and rerouting lines outside of the rack, as well as extending the existing rack to accommodate the remaining lines. Once this final routing has been decided, the majority of the piping can be installed, and integrity tested up to the point of final tie into the existing facility. Final tie-in is the only remaining activity to be performed during shutdown. A means to test each of the final field welds will need to be developed on a case-by-case basis to suit the conditions. Where possible, all the preparation work can be done during operations to limit the time to perform these final steps.

Civil/Structural
For Solution 2, the extent of reinforcement of the existing pipe rack will determine the scope for the civil/structural discipline. The reinforcement of the structure can be carried out during operations, as well as the foundation works, including pouring, as there are no vibrations that could be detrimental to curing. The Foundation Assessment Report indicates that no structural reinforcement of the existing tabletop structure is required. This is the only potential significant civil/structural scope envisaged for Solution 1.

Both solutions utilize newly allocated land for the positioning of the GIS substation and, for Solution 2, VFD E-houses. There is no significant difference in the sizes of the E-houses, however; as Solution 2 utilizes one large motor for the LP & HP MRCs, it results in one less E-House required. In Solution 1, E-houses are located closer to the motors, resulting in less cable length than Solution 2. It is also preferable to install VFDs as close as possible to the motors. This decreases the risk of signal loss and potential interference with frequency changes.

The power required for the installed capacity of the motors for Solution 2 is 10-MW more than Solution 1. The power consumption is, however, dependent on operational modes. All of the above can be used to compare the two solutions, but the major scopes that differentiate the construction effort are the rerouting of the pipe and resultant reinforcement of the existing racks for Solution 2, versus the demolition of the equipment and potential reinforcement of the tabletop for Solution 1.

CAPEX

The total installed cost of Solution 2 is estimated to be 71% higher than Solution 1. In terms of equipment costs only, Solution 2 is ~2.5x higher.

OPEX

The initial expectation is that the OPEX of Solution 2 will be lower, potentially by 3-5%. Much of this is attributable to the use of more modern compressor technology, as well as a high level of integration between the various components of the driver-compressor package. The main drivers of OPEX reductions are reduced power consumption and lower maintenance requirements for the compressors.

Scheduled Downtime

A major scope of demolition work for Solution 1 is to free the space on the tabletop to accommodate the new motor, as well as under the tabletop to reduce the overall load on the foundation. A lift plan is needed to determine the head room required for the setting of the new motors and the extent of the demolition of the existing shelter. The schedule duration of this scope should be determined by the execution strategy and, in particular, what manpower and demolition equipment is available.

Motor installation requires alignment to the compressors and full testing performed during the shutdown period. The exact duration of the execution of the setting and aligning is dependent on the execution strategy and whether this work is performed in parallel or sequentially. An estimated duration (per train) required for installation and commissioning of the motors for Solution 1 are as follows[1]:

- Installation time for the motor: 7-10 days
- Time for pre-commissioning tests for the complete motor-compressor module: 3-4 weeks for VFD and motor
- Time required for commissioning activities: 2-3 weeks
- Time required for carrying out Site Acceptance Tests for the motor: 2-3 days
- Alignment and coupling time with the existing compressor: 2-3 days
- Duration of performance test: 72-hour reliability test run

To accommodate the installation of the compressor skids for Solution 2, there is no significant demolition scope, however; the area identified for the multiple new refrigerant compression strings requires demolition of the existing feed gas compressors. This area is also identified as the area for multiple E-houses for Solution 1, so it requires demolition for both solutions. The demolition of this area and the installation of the E-Houses or compressor skids can be performed during facility operations and do not require a dedicated shutdown.

Execution Risks and Mitigation Measures

There are significant risks associated with the execution of Solution 1's scope of work. Demolition of large equipment and elevated works are inherently risky. For Solution 2, the greatest scope of work and most significant risk is associated with the extension of the existing pipe rack. Table 3 (Solution 1) and Table 4 (Solution 2) below identify some of the major risks and potential mitigations associated with both solutions.

Risk is scored based on two factors multiplied together: intensity of the impact caused by the risk and probability of the risk occurring. A higher score for an identified risk indicates a riskier event. Hence, a higher total score for a solution is a negative outcome in this assessment.

[1] Assumes one 12-hour shift per day

Table 3 - Major Execution Risks and Mitigation Measures for Solution 1

Risk Description	Category	Impact Description	Risk			Mitigation Notes
			I	P	Score	
Torsional instability between existing compressor and new motor	Mechanical	Elevated Cable Trays increasing loads in structure	5	3	15	Verify the schedule and identify when demolition works will be finished
Extensive demolition scope for compressor shelters will require a congested workforce to perform in the suggested scheduled duration	Safety	Recordable incident	4	3	12	Identifying what can be done prior to shutdown to alleviate congestion. Set limits of personnel within the demolition area
No data available for existing compressors	Mechanical	Delays in project implementation/extended shutdown period	4	3	12	Early engagement with OEM to assist in finding the relevant data. Collect all available reports on testing and performance of the existing compressors
Damage to existing compressor during removal of shelter for lifting of the motor	Demolition	Increase schedule duration	5	2	10	Ensure robust demolition plan is developed, identifying what can be done prior to shutdown to alleviate congestion and schedule pressure.
Areas that will be demolished (e.g., existing feed gas compressor) not available on time	Demolition	Delays in construction	4	2	8	Check during engineering stages, ensure availability of OEM vibration specialist during project execution
Unmapped underground interferences with desired cable trenches	Electrical	Major work to resize the cables and find alternative route	4	2	8	Investigation on existing underground structures to be performed on next projects phases by going through existing documentation of underground works + performing trial pit/slit trench investigation on site following the intended cable route.
Unmapped underground interferences during civil works to reinforce the pipe racks	Electrical	Major rework required to resize the cables and find alternative route	4	2	8	Investigation on existing underground structures to be performed on next projects phases by going through existing documentation of underground works + performing trial pit/slit trench investigation on site following the intended cable route.

Risk Description	Category	Impact Description	Risk			Mitigation Notes
			I	P	Score	
Damage to tabletop or existing equipment	Demolition	Increase Schedule duration	4	2	8	Remove as many auxiliaries as possible to allow maximum space to extract
Existing compressor rotor unable to resist the motor start up torque	Mechanical	Replace rotor	4	2	8	Check for rotor resistance at the next project stage, during the design stage
Existing foundations not able to withstand new loads	Civil	Aging of existing structures	4	2	8	Perform condition assessment of existing structures on next stage
No possible route through existing infrastructure to deliver new E-Houses from Material Offloading Facility	Logistics	Major delays to site work until route is cleared	4	2	8	Constructability engineer to walk through site to map delivery route and list adequate counter measures in case any interference is mapped. GIS should be transported not as full unit, but as separate combination of the units, which shall be assembled onsite and filled with insulation gas/blue air.
Extensive demolition scope for feed gas compressor will require a congested workforce to perform in the suggested scheduled duration	Safety	Recordable incident	3	2	6	Identifying what can be done prior to shutdown to alleviate congestion. Set limits of personnel within the demolition area
Existing relief system clashing with proposed cable routing	Electrical	Elevated cable trays increasing loads in structure	3	2	6	Routing needs to be evaluated more thoroughly
Loss of stability of the shelter structure during demolition could undermine the gantry crane	Demolition	Increase schedule duration	5	1	5	Ensure gantry crane is braced prior to start of demolition
Size of the E-houses is bigger and may not fit in the area available	Electrical	Delays to redesign the E-house and find new areas	5	1	5	Confirm all the dimensions with vendor before moving to the next phase
Electrical motor sizes are larger	Electrical	Delays to project due	5	1	5	Check variation in motor sizes between different vendors

Risk Description	Category	Impact Description	Risk			Mitigation Notes
			I	P	Score	
than designed and will not fit in the available space		to necessity to reevaluate space				
Inert gas inventories	Decom	Increase schedule duration	5	1	5	Ensure sufficient supply of inert gases is available before starting demolition/shutdown scope
Ground on area for e-house installation unstable	Civil	Major rework required to ensure ground stability	5	1	5	Proper reclamation project to be executed + onsite inspections and testing to ensure ground stability
Not enough room to install reinforcements under the tabletop	Civil	Major rework to project due to unfeasible reinforcements	4	1	4	Client to fully clear area under existing tabletops. 3D scan of the area to be conducted prior to engineering phase
Area for install new E-house not available on time	Electrical	Delays in the construction	3	1	3	Verify the schedule and identify when the area will be available

Table 4 - Major Execution Risks and Mitigation Measures for Solution 2

Risk Description	Category	Impact	Risk			Mitigation Notes
			I	P	Score	
No possible route through existing infrastructure to deliver new compressors or new E-house from Material Offloading Facility	Logistics	Major delays to site work until route is cleared	4	3	12	Constructability engineer to walk through site after motor definition to map delivery route and list adequate counter measures in case any interference is mapped
Existing pipe racks not able to withstand new piping/cable trays due to overstress/ structural damage	Structural	Major reinforcement works needed to strengthen pipe racks.	4	3	12	Site to be 3D laser scanned throughout intended pipe-routes to detect failures. Pipe racks to be checked for new loads prior to any work onsite. Some piping/cables to be routed outside on new racks
Interference between new piping and existing	Piping	Alternative loop placement or	3	3	9	Site to be 3D laser scanned throughout intended pipe-routes to detect interreferences during engineering phase

infrastructure due to loops/supports introduced by pipe-stress analysis		existing infrastructure removal to be proposed prior to construction				
Areas that will be demolished (e.g. ,existing feed gas compressor) not available on time	Demolition	Delays in construction	4	2	8	Verify the schedule and identify when demolition works will be finished
Interference between new cable routing and existing infrastructure	Electrical	Major rework required to resize the cables and find alternative route	4	2	8	Investigation on existing underground structures to be performed on next projects phases by going through existing documentation of underground works + performing investigation on site following the intended cable route.
Unmapped underground interferences during civil works to reinforce the pipe-racks	Piping/Electrical	Major work to resize the cables and find alternative route	4	2	8	Investigation on existing underground structures to be performed on next projects phases by going through existing documentation of underground works + performing trial pit/slit trench investigation on site following the intended cable route.
Unmapped underground interferences with desired cable trenches	Electrical	Major rework required to resize the cables and find alternative route	4	2	8	Investigation on existing underground structures to be performed on next projects phases by going through existing documentation of underground works + performing trial pit/slit trench investigation on site following the intended cable route
Existing foundations not able to withstand new loads	Civil	Aging of existing structures	4	2	8	Perform condition assessment of existing structures on next stage
Existing relief system clashing with proposed cable routing	Electrical	Elevated Cable Trays increasing loads in structure	3	2	6	Routing needs to be evaluated more thoroughly
Ground on area for E-house installation unstable	Civil	Major rework required to ensure ground stability	5	1	5	Proper reclamation project to be executed, as well as onsite inspections and testing to ensure ground stability
Size of the E-houses is bigger and not fit in the area available	Electrical	Delays to redesign the E-house and find new areas	5	1	5	Confirm all the dimensions with vendor before moving to the next phase
Area reserved for installation of new	Layout	Major delays to site work	5	1	5	Ensure that area is reserved for new compressors.

compressors no longer available		until route is cleared				
Inert Gas Inventories	Decom	Increase schedule duration	5	1	5	Ensure sufficient supply of inert gases is available before starting demolition/shutdown scope
Damaged or deteriorated flanges on tie-in points	Piping	Increase schedule duration	2	2	4	Tie-in points should be assessed prior to site construction, to verify their current conditions
Size of the E-houses is bigger and will not fit in the area available	Electrical	Delays to redesign the E-house and find new areas	3	1	3	Confirm all the dimensions with vendor before moving to the next phase
Area for install new E-house not available on time	Electrical	Delays in the construction	3	1	3	Verify the schedule and identify when the area will be available

Based on the tables above solution 2 is the less risky approach to the brownfield modifications for this real-world example.

Conclusion

In recent years, the LNG industry's increasing focus on decarbonization has led several brownfield liquefaction plants to begin exploring the possibility of replacing their gas- or steam turbine-driven compressors with E-drives. These projects are highly complex and carry significant execution risks. However, as this paper describes, in certain circumstances, if site conditions allow for the installation of new packaged compression strings and rerouting of piping to convenient tie-in points, these risks can be mitigated and scheduled downtime associated with the installation of the new electric motor driven compressors can be kept to a minimum or even potentially eliminated altogether.