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# Turbine Replacement by electric drive train

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## Abstract

Stricter emission regulations, higher process availability, improved fuel utilization and reduction of OPEX are some of the reasons to think about alternative ways to modernize old/conventional turbine trains. All these benefits could be realized by electric drive systems. Replacing a steam or gas turbine with an electric drive requires clarification and pre-engineering in order to analyze the existing drive train, electric grid, foundation, processing machine and process control system and to confirm the technical feasibility and savings, respectively the ROI. This white paper describes in general, the requirements needed to be considered as part of an "overall" solution in order to properly define the final technical concept and capture the technical as well as overall economic advantages.

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# Introduction

Steam or gas turbines in general are used to drive different processing machines. Specifically for the Oil & Gas industry, they are used to drive centrifugal compressors for example pipeline compression, refrigeration, and gas lift within a power range starting from kW up to around 90 MW for LNG processes. The figure below displays the equipment scope at a summary level. Depending on the converter technology and the grid optional, a harmonic filter might be required. The pure numbers of installed equipment of an e-drive system is higher compared to a turbine driven solution. Nevertheless an electric solution offers a high number of benefits which are explained in this white paper.

## A. Centrifugal compressor

Compressors are used to increase the pressure, respectively the isentropic heat of a specific medium. Depending on the requirements a compressor is operated within a defined area, which can be realized by different methods, like inlet or diffusor vanes, throttling (suction, discharge), recycling or variable speed. The last one is the most efficient and effective, as the driver provides only as much power as required. Therefore the drive unit must be controllable within the defined speed range of the compressor.

## B. Gas turbines

Gas fired turbines are split into aero-derivative and heavy duty. Both are common within Oil & Gas and have different advantages and disadvantages. The structure of both of these gas turbine types can be separated into three major parts: air compression, combustion chamber and turbine. A two shaft turbine splits the turbine into compressor and power part, compared to the single shaft version. Here the compressor turbine is driving the internal air compressor, and the power turbine on a second shaft provides the torque and speed on the output site.

The optimum power turbine speed depends on the volume flow input at the power turbine inlet. Increasing inlet air temperature means the efficiency, respectively the output power is decreasing.

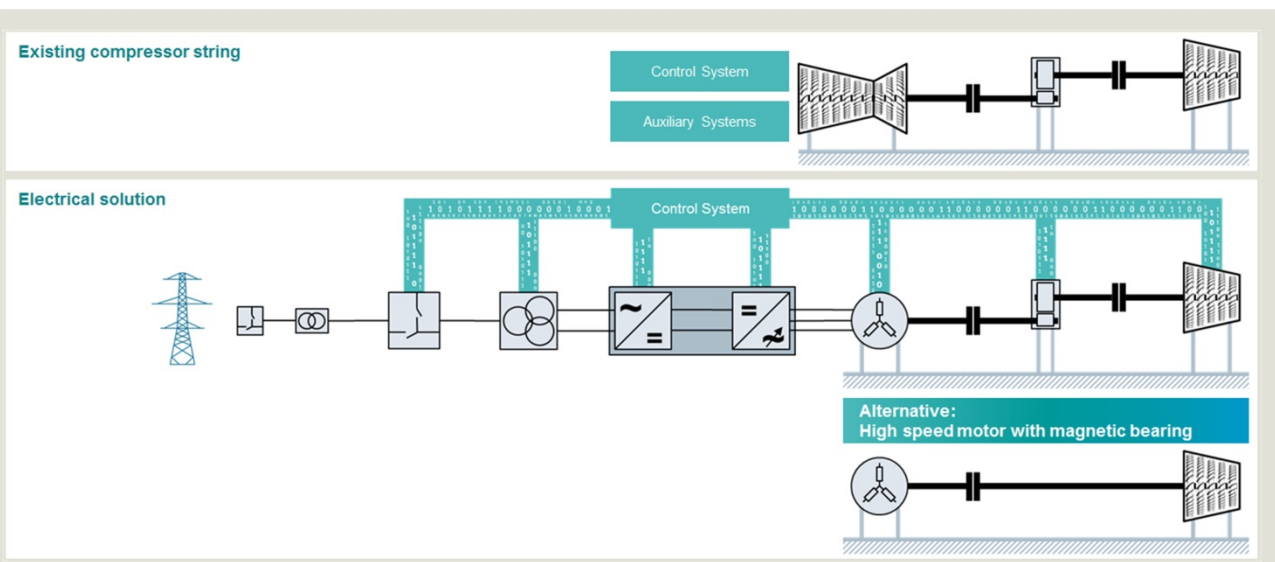
## C. Steam turbines

Next to gas turbines, steam turbines are common. Such turbines are operating in the so called Claus-Rankine Process. Many industrial sites usually have a steam network or steam is generated as a byproduct of a process on site. In these instances steam is favorably used to operate the compressor. In this case replacing it with an electric drive is typically not viable.

However there are exceptions that should be taken into consideration, for example the steam network, respectively steam balancing requires reduction of the demand, or efficiency increase on site leads to less available steam. Under these circumstances, an e-drive should be considered as a viable option.

## D. Electric drive train

An electric drive train consists of transformer, converter, so called Variable Speed Drive (VSD), electric motor and optional harmonic filter. Two different types of VSDs can be used: VSI or LCI. Using load commutating inverter (LCI) means normally a harmonic filter is required, based on the results of a grid study. Also for high power applications around above 25 MW such solution is required. Otherwise voltage source inverter technology (VSI) is applicable. Following two motor types are used: Asynchronous also called induction motor and synchronous motor.



# Comparison and potential benefits

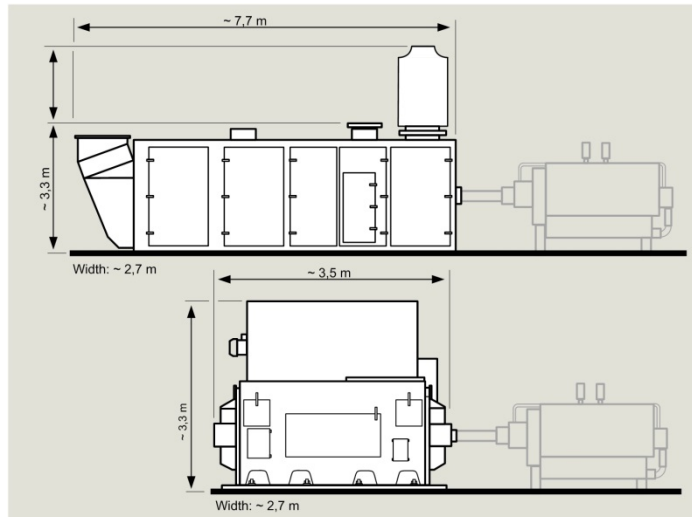
For this drive technology comparison example figures are used which are representative of common value. Depending for instance on design, ambient conditions, and application, the parameters will vary. Therefore this paper only presents indications, not absolute values.

## A. Emissions

Combustion of gas is a major source of nitrous oxides, (NO<sub>x</sub>), Carbon dioxide (CO<sub>2</sub>) and carbon monoxide (CO). CO<sub>2</sub> is regarded as a greenhouse gas with global warming consequences, while NO<sub>x</sub> is a regional pollutant causing acid rain and health complaints. Both emissions are under stricter regulations whereas the polluters often have to pay for the emission volumes in form of permits or carbon offsets. Additionally, more and more governments are either already taxing or considering taxing large carbon generators. Following example focuses on the carbon dioxide. A simple cycle gas turbine produces around 0,5 kgCO<sub>2</sub>/kWh. To compare this figure of carbon dioxide emission per kWh output, an ideal gas combustion, depending on the gas composition, has a value of around 180 - 200 gCO<sub>2</sub>/kWh. Using as example an 8 MW compressor gas turbine drive train, operating 8.000 hours per year would lead to an annual emission of 32.000 tones CO<sub>2</sub>. It is important to consider that emission control technologies, like lower flame temperatures or wet controls achieve reduction of emission but do so at the cost of lower efficiencies. By comparison, operating an electric powered drive train generates no emission on site. Next to renewable energy, by moving the combustion cycle for power generation, there is the additional benefit of moving the carbon generation cycle to a combined cycle turbine facility. This facility will operate under maximum efficiency / minimum emission with possible additional scrubbing and exhaust gas conditioning.

## B. Dimension and weight

Both drive technologies vary within dimensions and weight depending on manufacturer, type (aero-derivative and heavy duty, respectively induction and synchronous), application, explosion protection, cooling type and so on. It should be noted that for the electric drive a VSD, transformer and AMB a control cubicle may be required, but this equipment can be installed within a distance of up to 3.000 m cable length (even higher distances possible). Due to this fact the VSD is flexible for site planning and could be installed in an existing housing or in a container solution with separate foundation. The footprint of the electric drive solution in general requires less space next to the compressor compared to the turbine. Of course this has to be verified for each specific drive/foundation.



## C. Efficiency

The efficiency of a gas turbine depends on the type (aero-derivative or heavy duty), the design parameters and ambient conditions. Changing ambient conditions also leads to deviating operation parameters and changing efficiencies. The efficiency of an electric motor is specified for ambient conditions between -20 and 40 °C (or higher). By design, the efficiency of such motor is nearly constant over a wide ambient temperature range. Exceptionally high ambient temperatures require a correction factor for downsizing the motor during the design phase.

For the purpose of illustration, assuming a compressor efficiency of 83 % and an efficiency of 40 % for an aero-derivative, the gas turbine drive train has a total efficiency of 33 % for ideal conditions (heavy duty around 27 %). The electric drive train, starting from the transformer (99 %), VSD (99 %), electric motor (98 %) and same compressor efficiency of 83 % ends up at a total efficiency of 80 %. Considering a harmonic filter an efficiency value of 99,9 % can be assumed and by this neglected. Even if it is not relevant for the plant efficiency, including power generation (combined cycle with up to 65 % efficiency), transmission and distribution (95 %), the total efficiency starting from power generation is around 50 % for the e-drive train, and hence still higher compared to a single cycle direct gas turbine driven compressor.

$$\eta_{gas\ turb\ (aero-d)} * \eta_{comp} = \eta_{gas\ turb-drive}$$

$$0,40 * 0,83 = 0,33$$

$$\eta_{trans} * \eta_{VSD} * \eta_{motor} * \eta_{comp} = \eta_{e-drive}$$

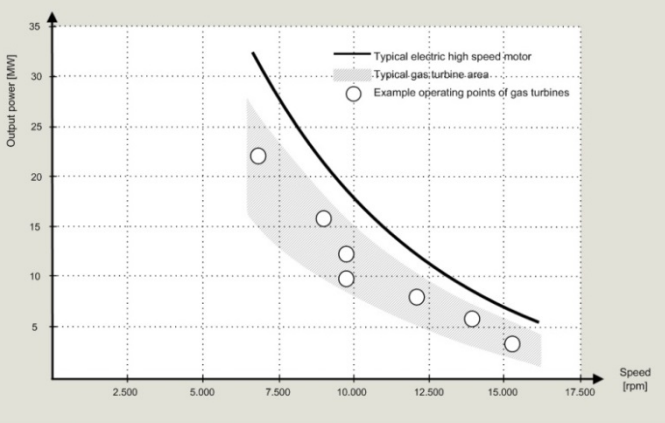
$$0,99 * 0,99 * 0,98 * 0,83 = 0,80$$

$$\eta_{gen} * \eta_{dis} * \eta_{trans} * \eta_{VSD} * \eta_{motor} * \eta_{comp} = \eta_{e-drive}$$

$$0,65 * 0,95 * 0,99 * 0,99 * 0,98 * 0,83 = 0,50$$

D. Operating points

Twin shaft turbines in general have a limited speed range of 0,5 or 0,7 up to 1,05 of the rated power, with a high impact on the efficiency and slow speed control response. E-drives can be operated within a wide speed range, starting from 0,25 up to 1,2 of the rated power, with a fast response for speed control and small variation in efficiency. Also as shown in the diagram below, electric high speed motors are able to cover typical gas turbines operating points regarding the speed and required power. Therefore the operating points of the different models of one gas turbine brand are used (white points in the diagram). The replacement can take place without any translation of speed and torque. The electric high speed motor curve represents the maximum speed for the specific output power, thus operating points below this line can be covered by direct electric motor drive.



Based on the wider and more efficient speed range of an electric drive solution, the following application example describes how these advantages can be used. The suction pressure in depleting gas fields declines over years. This requires continuously increasing compressor power. In a conventional compression design, a completely new additional compressor string is required when the production cannot be maintained with only one compressor. To minimize the capital expenditure, short CAPEX, a double shaft end motor can be used, allowing upgrade from one to two compressors. This enables a just-in-time high efficient adaptation of the compressor power without requiring a second driver.

To explain the theory of ambient and load impact, following Table is used. An 8 MW drive with full load and three-fourths load is operating 8.000 hours per year once at ISO conditions and once at 40°C. Based on assumptions for the efficiency the energy demand is shown. The gas turbine requires at full load and ISO conditions around 180 GWh, and 300 GWh for the higher ambient temperature. It can be seen that for the electric drive train the efficiency and hence the energy demand does not change regarding these ambient temperatures. The energy demand of an e-drive for this example is at least 30 % compared to the turbine demand. This energy savings increase further for part load and higher temperatures.

		Gas turbine		Electric drive train		
		Unit	full load	part load	full load	part load
operating hours	h/year		8.000	8.000	8.000	8.000
output power	kW		8.000	6.000	8.000	6.000
ambient temp. 15°C (ISO)	efficiency	%	35%	28%	95%	94%
	energy demand	GWh	~ 180	~ 170	~ 65	~ 50
ambient temp. 40°C	efficiency	%	21%	18%	95%	94%
	energy demand	GWh	~ 300	~ 270	~ 65	~ 50

Table: Energy demand (different load, ambient temp.)

E. Start-up & stop process

Aero-derivative gas turbines are able to start within around 10 min, without impact on life cycle. For heavy duty types the start from idle speed is around 10 to 15 min. Starting from operation at full load until stop roughly the same time as for the start could be assumed. Depending on the mass the heavy duty turbine maintenance shut down take even longer, up to a few hours, because of the cooling process. Furthermore if there is no restart within a defined time, a full machine cool down must take place.

Assuming again an 8 MW electric high speed motor with 14.000 rpm and a moment of inertia of 20 kgm<sup>2</sup>, directly operating a centrifugal compressor (Neglecting the limitations for the compressor start process and focusing only on the e-drive), the start-up time is less than 4 minutes. After the start signal the VSD limits the current, depending on the motor nominal current value and runs up to the operating point (here 7,6 MW, 13.500 rpm). Assessing the stop process an electric motor for compressor applications usually does not require active braking, concerning the motor or VSD. After the stop signal the motor coasts until standstill. The number of start & stops processes within a short time is almost only limited by the cooling capacity of the VSD and motor. Usually repeated starting within a short time is no problem from the driver's point of view.

As a result the e-drive train provides a simple and fast start and stop process. This behavior affects also the downtime regarding maintenance.

F. Maintenance

Neglecting the auxiliary equipment, like purging and lubrication systems. For the turbine maintenance schedule so called equivalent operating hours, short EOH, are usually taken into account. This value is calculated via the data of operating hours per year, the stress factor (type of load), the number and type (normal, fast) of start / stop. A higher

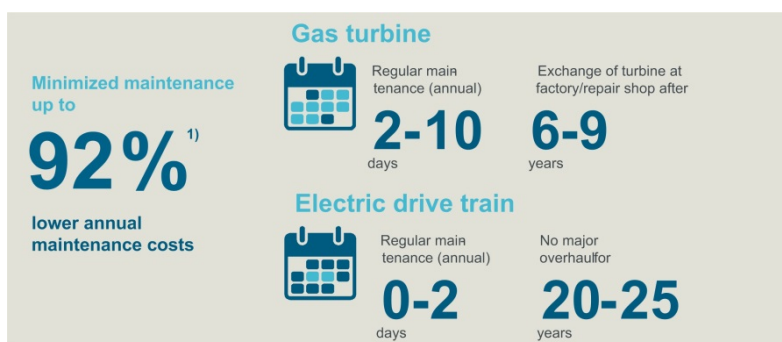
EOH means higher maintenance effort. Further factors like fuel quality, age of the turbine and performance parameters have to be considered also. It is important to separate aero-derivative and heavy duty. Based on these parameters and the visual inspection, the required maintenance and overhaul of turbines is defined. The service can be separated into three major categories:

- **Minor overhaul:** remote online check, change of the filters, bore scope inspection of compressor casing, vanes and blades, burners, combustion chamber, turbine vanes and blades. Inspection of: auxiliaries, driven equipment, main gear and coupling.  
Each year;  
on site;
- **Hot path inspection:** everything out of the minor overhaul, including the inspection of the hot path.  
Depending on operation parameters;  
on site;
- **Major overhaul:** everything out of hot path inspection, the turbine is general overhauled.  
Depending on operation parameters (every 6...9 years);  
Not on site;

It can be assumed that for an aero-derivative within the first 100.000 operating hours 40 days and for the heavy duty between 100 and 140 days are required. That means average around 3 days, respectively 8 days per annum.

Assessing the maintenance of e-drive with magnetic bearings, a yearly visual inspection, performed during operation, is recommended. Such driver is independent of an operating hour (EOH) calculation for the maintenance plan. Thanks to their non-contacting design, magnetic bearings are practically maintenance-free. Furthermore no oil system has to be checked and maintained. Roughly every four years a more detailed motor inspection should take place, including for instance borescope inspection and isolation resistance checks of rotor and stator and the cooling system, which service, depending on the motor, can take up to 3 days. For the VSD it is recommended to consider one day for service each year. Additionally visual inspection of the fans, water connection, if water cooled and functions test like for the power bank should be performed. Under favorable ambient and operating conditions the maintenance intervals can be significantly extended after the first year.

An e-drive train needs no general overhaul within around 20 - 25 years, depending on ambient and operating conditions. Inspection and service during this time period can be performed on-site and within a few days only, which results in a low maintenance drive technology, compared to a turbine. Furthermore, due to drive train analysis and visual inspection during operation it is possible to operate for up to 4 or even 5 years without shutdown. Less downtime, less effort, leads to less cost and higher availability.



### G. Reliability / Availability & Stand by

For reliability, availability or mean time between failures (MTBF) different definitions respectively calculations are common and hence hard to compare. Reliability itself is defined as the probability that an item can perform a required function under given conditions for a given time interval (IEC 60050-191). Availability can be described as possible operating time considering all scheduled and unscheduled downtimes, like service or failure.

The reliability of turbines increased during the last decades, especially because of the aero-derivative type. However the installed base of turbines within the Oil&Gas industry is aging, which lead to decreasing efficiency and reliability values for the installed fleet. Using turbines means operating many rotating parts, high temperatures and high stresses for components, which leads to a low value of reliability (compared to e-drive). Gas turbines have often identical core engines with commonality of spare parts, which allows spare part management over a regional pool. Short spare part delivery time, and reduced spare parts costs are feasible. However, due to the amount of components, it is still required to have more spare parts compared to the e-drive.

If a critical process has to be driven, considering the storage of the critical parts, like spare rotor or even a spare motor on site, increases the availability with a small invest compared to losses because of unplanned downtime. Such solution should be compared to the spare part management effort for gas turbines individually.

Considering the availability it is possible to operate the e-drive years without downtime. Such a drive is a sophisticated technology with less rotating parts. Even so it is designed for high availability, specific VSDs are using bypass power cells, which bypasses faulty cells automatically without shutdown. During shutdown it can be changed within minutes, due to the design as closed component to plug in.

Compressors and gas turbines can fail during a starting process, for example if the required speed is not reached within a defined time. Such situation leads to starting process breakup, cooling time and re-start. Using an e-drive,

out of an electrical point of view, the starting process is uncritical.

Without going into detailed description of the methods, assumptions and failures, gas turbines have a common reliability value of around 97 - 98 % (availability of around 95 - 96 %), compared to possible values of 99,9 % for reliability and availability for electric drive trains. For a reliable statement regarding availability of the electric drive train the electric power supply has to be considered, which leads to a very specific calculation and comparison of each individual site.

#### H. Total costs of ownership

For a comprehensive economic assessment of turbine and e-drive the total cost of ownership are compared, thus the CAPEX and OPEX for the planned life time. It should be distinguished between two different investment calculations - green field (new installation) or brownfield (replacement of old existing turbine). For a green field installation the CAPEX between a new turbine and a new e-drive train has to be considered in addition to the operation costs. The investment in a new drive at a brownfield case has to depreciate itself via the savings. Here the key criterion is the return on investment (ROI).

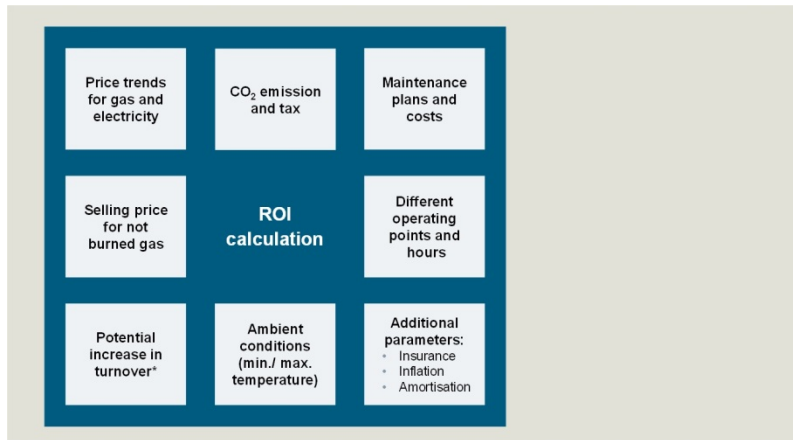
The CAPEX for the drives are depending on many factors. As a consequence it is not possible to bring it down to one value, like comparing the invest per output power [€/kW]. Regarding the OPEX, following topics have to be analysed for turbine and e-drive separately:

Next to the energy source price, gas and electricity, the operating points are important. Comparing the full load efficiency does not represent the operating conditions during life time. Such study of an existing site brings the benefit of utilizing the real operating data from the past, in specific the different loads over time and ambient conditions of the last year. On the basis of this site data the specific efficiencies for the different load, the required power, the operating time and the energy costs can be calculated. Another parameter for some applications (like gas pipeline compressor station) is to use electricity means to sell the not burned gas, hence potential to increase the turnover.

As mentioned already, the turbine and e-drive maintenance verifies. Considering this difference it is worth to have a closer look. A comprehensive approach will be to compare long term service agreements, short LTSA, for both technologies. Such agreements will include the maintenance schedule, effort, required man power and spare parts. Such comparison indicates that the e-drive has an easier maintenance concept and brings financial benefits due to the explained technical advantages.

Depending on the required uptime, based on the reliability and availability of both drives, values for planned and unplanned downtime should be considered also. Redundant

systems require a more detailed consideration because of the alternate up and down time.



CO<sub>2</sub> emission is a local parameter. For the respective regions the emission of the turbine has to be taken into account and multiplied with the tax per ton CO<sub>2</sub> or respectively payment for the emission. Parameters differ from region to region.

Insurance costs for a gas turbine can be high due to fire hazard, compared to the possibility for a pressure resistant casing and non-sparking electric motor design. Also the flexibility to install the VSD within 3000 m cable lengths, means installation in non-hazard is possible. This parameter has to be checked and possibly deviations for the insurance fee calculated.

The amount for the investment has to be evaluated, starting for the first analyses with estimations and budget values after detailed technical studies.

# Scope of work

The Analysis, Pre-FEED or FEED to replace an existing gas turbine in a brown field needs an actual recording of current drive train and site data. Talking about green field the same working packages have to be gone through, and checked if relevant or not. The following picture shows the major topics have to be analyzed.

## A. Processing machine / Pre conditions

Reuse of the compressor requires a data acquisition for designing the suiting new drive and furthermore to create out of the whole drive the model for torsional and string calculations. The same data acquisition applies for the existing foundation, the drawings have to be checked and whether any changes during life time were executed. Also site drawings should be analysed concerning the available space for additional new equipment like transformer or e-house, and also e.g. crane for the revamp work.

## B. Infrastructure

It has to be considered whether the existing equipment like re-cooling unit or lubrication system can be reused, and which possible changes are required. Also it is possible to consider the installation of an e-house, which leads, due to a pre-mounted and tested equipment (VSD, switchboard, MMC, etc.) to less effort and risk on site. Next to the transformer housings, the cable tracing and e-house foundation could be prepared / executed in advance during operation. Such options have to be considered within the basic design phase.

## C. Engineering & Studies

Before considering the drive train itself the availability and capacity of the electric energy source has to be inspected. Therefore based on the required load and the data of the existing grid, a grid study including network concept, harmonics, power factor corrector, protection philosophy, safety concept, grounding and optional filter design (depending on the used drive) should be performed. If required also the connection of the site to the electric grid could be considered.

Analyze the new system (motor, compressor) regarding foundation and string should also be part of such pre-engineering. Starting from measuring the existing foundation and data capturing of the compressor, creating calculation models, a foundation, string and vibration analysis can be performed. Within this stage countermeasures could be defined and implemented for the motor design to keep the adjustments on site as small as possible. Further working packages within this stage are

cable planning, combine consumption list of reused and new equipment/consumers and so on.

## D. Electric drive train

On the basis of operating data from the past or considering prospective growing demand, an electric drive train is engineered according to the parameters (speed, torque, footprint, etc.). If space is available within a building an existing room can be used for the VSD cabinets (bring in concept has to be considered), otherwise an e-house can be installed on site.

## E. Process Control System

For the new concept of the drive train, the concept of the existing process control system must be adapted and configured. This requires expert knowledge on the existing system on site and the control systematic of the VSD which has to be attached and configured to the overall control unit. A detailed engineering process on this working package has to define the interphase between new and existing system.

## F. Project Management

Summarizing the required data, organizing a site survey, capturing the information such as available space, compressor details, electric grid and existing process control unit with focus on the interface, are representing the first steps of the project manager within such study phase. After execution of all further described working packages, like drive train design and foundation analysis the site activities have to be worked out in a preliminary form to plan dismantling, installation, commissioning, required tools, man power, time schedule and last but not least the costs. 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.

## G. Replacement budget and ROI calculation

The investment consists, next to the equipment costs, of the civil work, turbine dismantling, installation and so on, should cover all costs starting from the FEED until the new e-drive runs up (after acceptance test). The OPEX of the existing turbine has to be compared with the designed e-drive train OPEX over the life time including case studies for possible gas and electricity price trends.

Studies	Control Systems	Electrical Systems	Auxiliary Systems
<ul style="list-style-type: none"> <li>Harmonic study</li> <li>Network study</li> <li>Foundation study</li> <li>Rotor dynamic study</li> </ul>	<ul style="list-style-type: none"> <li>Station control system</li> <li>Unit control system</li> <li>ESD system</li> <li>SCADA system</li> <li>Fire and gas detection</li> <li>Instrumentation</li> <li>Power management system</li> <li>IT Solutions</li> <li>Telecommunication systems</li> <li>CCTV &amp; PAGA systems</li> </ul>	<ul style="list-style-type: none"> <li>Electric motors</li> <li>Drive systems</li> <li>Harmonic filters</li> <li>Power Transformers</li> <li>HV, MV &amp; LV Switchgears</li> <li>LV MCCs</li> <li>UPS, DC</li> <li>HVAC</li> <li>Solar power system</li> <li>Indoor and outdoor lighting</li> </ul>	<ul style="list-style-type: none"> <li>Trace heating</li> <li>Cathodic protection</li> <li>Gear boxes</li> <li>Oil supply systems</li> <li>Cooling systems</li> <li>String base frame</li> <li>Container houses</li> </ul>
Services			
<ul style="list-style-type: none"> <li>Project management</li> <li>Engineering</li> <li>Interface handling</li> <li>Installation</li> <li>Commissioning</li> <li>Training</li> </ul>	<ul style="list-style-type: none"> <li>Long term maintenance</li> <li>Remote on call service</li> <li>Spare part handling</li> <li>Repair services</li> </ul>		



## Conclusion

*“The electric light did not come from the continuous improvement of candles”* (quote from Oren Harari), in other words the electric drive train offers the flexibility to meet changing demands, lowers the environmental impact, offers a higher level of availability and comes along with higher efficiency. But such change from one drive technology to another requires a detailed pre-engineering. Therefore different working packages of various fields have to be considered to define the technical feasibility, and elaborate the benefits. To obtain a reliable study an experienced partner with equipment and project knowhow should be involved to consider the entire scope. Nevertheless the potential of such drive change is extensive and is worth the effort.

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