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FAST START AND CYCLING HRSGS: SIEMENS DRUMPLUS™ TECHNOLOGY

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ABSTRACT

Fluctuating renewable power generation is structurally changing the electricity markets in almost every country or region. In the past, traditional Gas Turbine Combined Cycle Power Plants (CCPPs) were practically only running in base load operations, providing electricity to the grid for a large part of the year, and only a limited number of start/stops had to be made per annum. However, the market changes require CCPPs to adapt to a new reality. The market demands quick and flexible power generation, especially from fossil fuel power generation capacity.

Traditional Large CCPPs, with F-class or higher capacity gas turbines, are limited in both the startup time (which can be up to an hour or more) and the number of starts/stops. Until a few years ago, most of the CCPPs in Europe where running for more than 5,000 hours per year and where only stopped and started for 50 – 100 times annually. Now, CCPPs are running only a couple of thousand hours – if being lucky - and have to be stopped and started often on a daily basis. This new world gives huge challenges to large CCPPs, but it also provides new opportunities.

The need for flexibility and ever more powerful gas turbines requires HRSGs that are robust, have large pressure parts and are capable to start up fast. These characteristics seem to conflict as larger and thicker pressure parts do not create flexibility, but a lack thereof.

However, Siemens HTT fast start design ensures unrestricted GT ramp-up and long lifetime, also for the latest high output GT models. This means that the HRSG is no longer limiting the gas turbine in CCPP operations, and it can ramp-up as fast as possible.

The HRSG is designed so that peak stresses are significantly reduced. This results in a boiler that is capable of rapid cycling operation. In the DrumPlus™ HRSG, the High Pressure drum has a small wall thickness as a result of the small drum diameter, and nozzle sizes are minimized, allowing for unrestricted GT ramp-up. Key is the external location of the secondary water-/steam–separators, allowing an optimal separator design without the limits set by the confined space in the drum. The El Segundo CCPP in California is the world's first large CCPP with fast start and cycling HRSG capabilities of its kind.

The fast start power plant offers higher plant efficiency and significantly more kilowatt-hours for commercial use during the first hour of its operation. Fast ramp up also allows gas turbines to reach low NOx and low CO operating loads quickly. As a result, demanding environmental permits are complied more easily and a quicker response to power demand is achieved.

INTRODUCTION

With the energy market changing quicker than ever, the global power markets are also fundamentally undergoing a change to a new system. Renewable electricity generating sources as wind and solar are influencing how the power markets worldwide are being organized, as well as how existing and new electricity generating sources have to operate. Combined Cycle Power Plants can play a role in the globally changing power markets, but they have to adapt to new market requirements. This paper will go deeper into the needs of today's market, as well as into the future's, based on the California Electricity markets (called California Independent System Operator (CAISO) market) which deals with a great deal of renewables generation and is exemplary for what other market might face in the future.

Further analysis will describe the impact on designing HRSGs for Combined Cycle Power Plants. The future needs are of course very unpredictable, and the uncertainty of the future is clear, however main trends are illustrated which will impact HRSG-design. Is the traditional design approach, which has been used for decades now, sufficient for today's market and what has to change to meet future market requirements? A duck curve is used to explain expected changes in operating regime which directly impact the requirements on the GT, and thus also on the HRSG.

What are the challenges for the HRSG, and which components need extra attention in this process of redesigning a future-ready HRSG? Critical components, like the high pressure drum, are always a first to think about, and are of course important, but it goes beyond that. It is not only about looking at different critical HRSG components and enhancing those, but the whole HRSG system will have to be redesigned to purpose. Fast start and cycling operations will become key, but what are the benefits of having a fast start and cycling HRSG-design? Three main benefits are discussed in depth.

The DrumPlus™ technology has been developed by Siemens Heat Transfer Technology (formerly known as NEM Energy), and is the proven solution for fast start and cycling operations. The technology is explained on the main topics it addresses throughout the HRSG. The technology is already in successful commercial operation for two units in the El Segundo Combined Cycle Power Plant in California, and with nine units under construction DrumPlus™ is the globally leading HRSG-technology for fast start, unrestricted GT ramp-up, and cycling operations.

NOMENCLATURE

The following names and abbreviations are used throughout this paper:

Bar	A metric unit of pressure
CAISO	California Independent System Operator
°C	Degrees Celcius
CCPP	Combined Cycle Power Plant
CO	Carbon Monoxide
CO2	Carbon Dioxide
GT	Gas Turbine
GW	Gigawatt
HP	High Pressure (section of the HRSG)
HRSG	Heat Recovery Steam Generator
HTT	Heat Transfer Technology
IEA	International Energy Agency
IP	Intermediate Pressure (section of the HRSG)
Low cycle fatigue	Progressive localized structural damage
LP	Low Pressure (section of the HRSG)
MW	Megawatt
MWh	Megawatt hour
NOx	Nitrogen Oxide
Psi	Pounds of pressure per square inch
PV	Photovoltaic
RH	Reheat (section of the HRSG)
SC	Simple Cycle (only GT operations)
SCF	Stress Concentration Factors
SCPP	Simple Cycle Power Plant
SCR	Selective Catalyst Reduction
SH	Super Heater (section of the HRSG)
TWh	Terawatt hour
3P RH HRSG	3 Pressure level HRSG with Reheat

I. CHANGING POWER MARKETS

The penetration of renewable electricity generation into the electricity markets is going very fast at the moment. On a global level, solar and wind play an increasingly important role in meeting the annual additional installed power demand. According to the International Energy Agency (IEA), solar and wind are booming and during 2016, for the first time, solar PV additions rose faster than any other fuel, surpassing the net growth in coal or gas (IEA, 2017).

Technology / Fuel	Net capacity additions (GW)	Retirements (GW)	Total additions (GW)
Coal	57	26	83
Natural Gas	21	12	33
Renewables	164		164
Renewables of which Solar PV	74		74

***Table 1**: 2016 global capacity additions – coal and gas versus renewables*

At the beginning of this century, only 18 years ago, renewable electricity generation, especially wind and solar, played almost no role at all in our energy mix. In the year 2000, only about 1 GW of solar PV was installed worldwide, and roughly 17 GW of wind power. During the first decade of this century, wind and solar started to develop, but real growth has come during the last years, from 2010 onwards. In just six years time, the total global installed solar PV capacity rose from 39 GW in 2010 to roughly 299 GW in 2016. This incredible growth has surprised many, and it was certainly not anticipated during the beginning of this century.

More interesting even is the expected installed capacity in the future as that gives a good indication of the market situation in the future environment. The IEA makes these future predictions in their forecast scenarios. In their so-called Sustainable Development Scenario (where they predict the total installed capacity in 2030) wind and solar are estimated to play a key role in the electricity supply mix, and they will account for the majority of the total capacity additions to 2030. In 2030, after natural gas, solar PV will have the highest installed global capacity, surpassing natural gas in the first years during the thirties of this century. According to the International Energy Agency (IEA, World Energy Outlook 2017), in 2040, the top three power generating sources will be solar PV (3246 GW), wind (2639 GW), and natural gas (2297GW).

Technology / Fuel	2000	2010	2016	2030
Coal	1144	1633	2020	1686
Natural Gas	796	1371	1650	2032
Oil	443	435	443	274
Nuclear	384	401	413	586
Hydro	787	1027	1241	1723
Other renewables	49	100	145	385
Wind	17	181	466	1706
Solar PV	1	39	299	1846

***Table 2**: Global installed capacity in GW by year*

Also on the generation side, renewables are contributing significantly to the overall electricity production. From virtually no supply from wind and solar in 2000, now about the same amount of electricity is generated by wind as by oil. In only twelve years from now, the total renewable generation, wind, solar and other renewables, will be the number one ranking source of electricity production according to the Sustainable Development Scenario presented by the International Energy Agency in the World Energy Outlook in 2017 (IEA, World Energy Outlook 2017). When looking even further down the road, it is the IEA’s expectation that Wind will become the single largest source of electricity in 2040. Solar power production will increase 17-fold compared to the 2016 level, while fossil fuels are expected to have declined significantly in their contribution to the global electricity supply, with natural gas first increasing to 6950 TWh in 2030, thereafter declining to 5585 TWh in 2040.

Technology / Fuel	2000	2010	2016	2030
Coal	6005	8664	9282	4472
Natural Gas	2753	4822	5850	6950
Oil	1259	995	1006	412
Nuclear	2591	2756	2611	4295
Hydro	2619	3443	4070	5688
Other renewables	217	444	667	1804
Wind	1	341	981	4193
Solar PV	1	32	303	2732

***Table 3**: Global electricity generation in TWh by year*

During 2007 only 16 thousand MWh in the USA was generated by solar PV while during 2017 this figure rose to 49,688 thousand MWh; an enormous increase. Wind power generation increased from 34,450 thousand MWh in 2007 to 254,254 thousand MWh in 2017 (EIA, Net Generation from Renewable Sources, 2018). When looking at all the fossil power generation together (excluding nuclear), the total supply in TWh has been decreasing since 2008. The total decrease from 2008 to 2017 has been as much as 14%, with the period from 2015 to 2017 accounting for a significant portion of 8%. It can be concluded that the overall contribution of renewables is accellerating and that the accelleration of renewables impacts the total contribution of fossil power in a negative way. This trend is expected to continue, and is likely getting much stronger.

II. IMPACT ON CCPPS

As the sun only shines during day time, and wind doesn't blow always, the renewable power generation sources have a strong influence on the grid. The intermittent and stochastic character of solar radiation for example, makes the work of an energy manager difficult, especially when maintaining the production/consumption balance within an electrical grid (Notton, 2018). And as the consumption of electricity cannot be adjusted quickly, the production will have to be adapted to the new market situation.

Already in 2011, Klimstra and Hotakainen described (Klimstra, 2011) the effect of solar PV output on system balancing. At the time, Germany had, as a percentage of the total capacity, the highest percentage of solar PV connected to the national grid. Based on an analysis of solar PV output on five days in 2010 in Germany, it can be concluded that solar PV shows big seasonal differences in their electricity production. In the darker winter season for instance, solar PV hardly produces any electricity, while in the sunny summer season, solar PV panels can almost reach their nameplate capacity. Also during the day, there are huge differences. Typically the highest output is reached during the solar peak, between 12:00 and 14:00 hours, and especially during the summer season when the solar radiation is strongest.

In order to be able to discuss the impact of the changing market, and especially the strong penetration of intermittent power generating sources, on existing and new CCPP, the regional Californian market will be further analyzed. It is one of the markets that has been dealing with a significant amount of renewable energy coming online during the last years. The market is called the California Independent System Operator, also known as CAISO. The CAISO electricity grid delivers wholesale electricity to local utilities for distribution to approximately 30 million customers. The grid covers most of California, as well as a portion of the state of Nevada. Every day, CAISO facilitates over 28,000 market transactions to match buyers and sellers of electricity.

An appropriate way to analyze the impact of renewables to the other generating sources, as CCPPs, is to analyze the so-called duck curve. The curve is calculated as follows: **total generation load – total renewable load = total net load**. Following the formula, the total net load is the total generation required from non-renewable power generation. The total net load over the course of the day is called a duck curve, because it resembles the shape of a duck. In this paper, two main items from the duck curve will be examined from an average day in March in the years 2012, 2017, and the expectation for 2020, based on the current planning. The first item is the grid necessity for base load versus the flexible load power generation. The second item is the required load ramp rates during an average day.

In the CAISO-grid, during 2012, only 5% of the total power generation was supplied by renewables. In this situation, shown in figure 1 below, the amount of base load power supplying electricity in an average day in March, was approximately 17 GW, while the amount of flexible generation amounted to about 8 GW. The ramp rates in the morning and in the evening peaks were between 15MW/minute and a maximum of 32 MW/minute. In this situation, a large CCPP of 800MW would require to startup within 27 (to meet the highest ramp rate) to 52 minutes (to meet the lowest ramp rate) time in order to meet the required ramp rates. The body of the curve still outlines a flat duck.

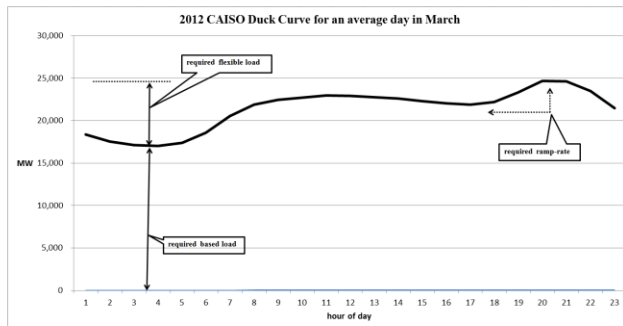

***Figure 1**: 2012 CAISO Duck Curve average day in March*

In 2017, the penetration of renewables, especially solar, but also wind, has already increased from 5% in 2012 to 23%. As can be seen from figure 2 in the below graph, this has a serious impact on the net load. The non-renewables have to deal with higher differences of load requirements throughout the day. Firstly, the amount of base load power generation has decreased from 17GW to about 12.5GW, while the need for flexible power generation has increased from a total of 8GW to 12.5GW. In addition, the ramping requirements during periods of increased dispatchable power demand, basically during the period the sun goes down, have accelerated. Between 5pm and 6pm the required ramp rates are close to 70 MW/minute on an average day in March, and are even higher for specific days and time periods. The duck shape is now appearing in the curve.

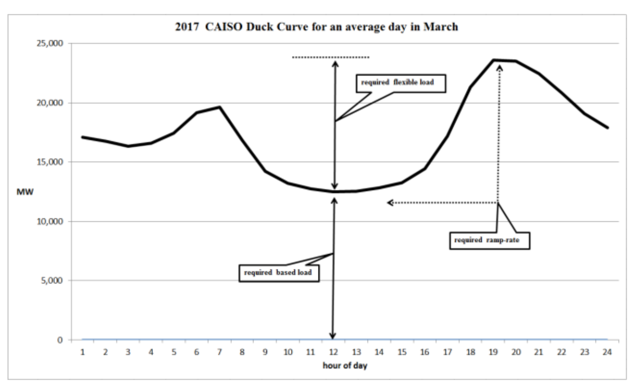

***Figure 2**: 2017 CAISO Duck Curve average day in March*

In 2020, only in a couple of years from now, it is expected that even more renewables have been installed and will be supplying electricity to the grid. The total renewables penetration is expected to grow from 23% in 2017 to 33% in 2020. The amount required for base load power is expected to decrease further from 12.5GW in 2017 to approximately 8 GW in 2020, while the flexible power generation supply will increase from 12.5GW in 2017 to roughly 17GW in 2020. The required ramp rates are also expected to increase further. Especially in the steep increase between 5pm and 6pm, the ramp rates are forecasted to be close to 130MW/minute, and can even become higher for specific days and time periods. Now, the contour of the duck in the curve is clearly visible.

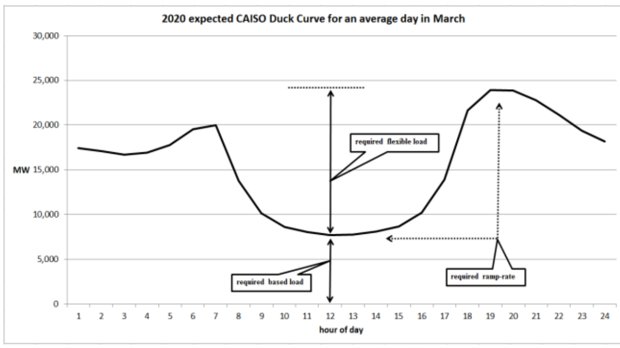

***Figure 3**: 2020 CAISO Duck Curve average day in March*

Base load power can be generated by CCPPs, but typically base load power is generated by non-dispatchable generation sources, which cannot be shut off and on easily. These are sources like nuclear power plants, some cogeneration plants, as well as many coal fired power plants. In 2014, these non-dispatchable units had a total capacity close to 15 GW in the CAISO grid (Bouillon, 2014). A need for more flexible power could put extra pressure on the closure of old coal fired or nuclear power in favor of flexible power generation, such as CCPPs.

The CAISO duck curve shows the new reality for many other regional electricity markets that will deal with an increase in renewable power generation in the future, and as such it can be concluded that markets globally will see the following main trends from the exemplary CAISO-market in the near future:

1) More flexible power generation is required to be able to follow the future net load curves
2) Flexible power generation will face strong cycling operating regime with daily starts/stops
3) Flexible power generation needs to be able to ramp up as quickly as possible

III. REDESIGNING HRSGS FOR THE FUTURE; THE CHALLENGES

As concluded from the CAISO duck curve analysis, CCPPs are increasingly being called upon to be more flexible in operation, both in terms of startup capability as well as in cycling performance. This requirement for plant flexibility is a challenge for, and especially the lifetime of, the HRSG. More starts mean more stress cycles and faster starts lead to increased local and global temperature maldistributions, resulting in increased thermal stress. The desire for high plant efficiency makes the challenge even larger.

Higher plant efficiency requires an increased steam pressure and temperature in the HRSG which generally leads to thicker pressure parts, resulting in increased thermal stress. This leads to increased low cycle fatigue damage and larger expansion differences in and between boiler parts. The trend from base load plants towards fast cycling plants with increased plant efficiency makes the lifetime of the HRSG currently a bigger issue than it was in the past. This new reality forces to adapt the way HRSGs are designed, and two of the main challenges will have to be addressed accordingly:

i. Low cycle fatigue

Low cycle fatigue is the most important damage mechanism for cyclic behavior as it is caused by cycling/cyclic stress events. The amount of low cycle fatigue damage which occurs is determined by the number of cycles that a component is exposed to, the stress range in each cycle and the characterizing temperature level of each cycle. The stress range is determined by mechanical and thermal stress and by the combination of a startup, followed by a shutdown (figure 4). The mechanical part only depends on the minimum and maximum pressures in the cycle whereas the thermal part is very dependent on the actual operation of the plant (i.e. transients during both startup and shutdown). Combined with the fact that the local heat transfer can have a significant effect on the temperature distribution in the component, this makes thermal stresses particularly hard to predict.

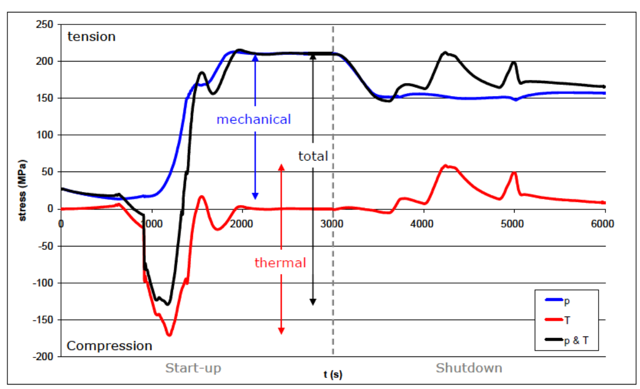

***Figure 4**: the stress range for fatigue is determined by mechanical and thermal stress and by the combination of a start-up followed by a shutdown. Example of the stress behavior during hot start and shutdown in a SH header designed for cycling operation.*

The material and the geometry of the component are very important aspects for the resulting fatigue damage as some materials can withstand higher stresses than others and the geometry can have a large impact on the resulting stresses. Important aspects of the geometry are the (wall) thickness and the shape. Stresses are concentrated at specific locations, such as the inner edge of a hole in a cylinder to cylinder connection (see figure 5). The stresses in this hole can be related to those in the cylinder by means of so-called Stress Concentration Factors (SCFs). As the SCFs are significant, cylinder to cylinder connections are important locations to investigate during HRSG design, i.e. the highest stresses are found at these connections. Examples of critical connections are:

- HP Drum nozzles
- HP SH header nozzles
- HP main steam line and manifold nozzles

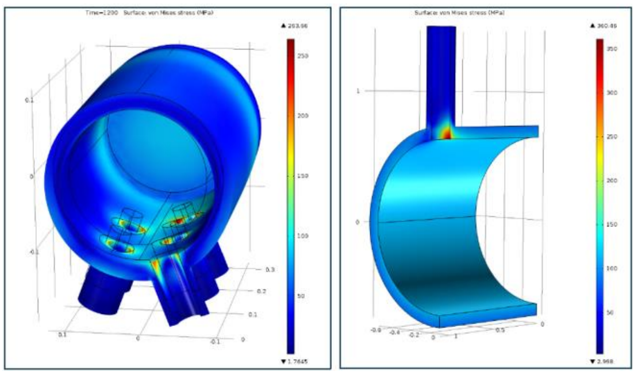

Figure 5*: Stresses at the inner edge of a hole (cylinder to cylinder connection).* ***Left****: thermal stress concentration in a SH during start-up.* ***Right****: mechanical stress concentration in a drum during steady state operation.*

ii. Expansion differences

Temperature and/or material differences can result in large distortions and high stresses. When the expansion is restricted (e.g. when there is no sufficient flexibility) this can lead to quick failure by excessive plastic deformation (e.g. by excessive tensile stress or buckling) or failure by means of (low cycle) fatigue for lower stresses. Such large distortions and high stresses can both occur within components (e.g. different rows in tube bundle) and between components (e.g. between tube bundles). High stresses and consequent failure can be prevented by controls (minimize temperature differences) and design. For instance, by allowing expansion and expansion differences through implementing flexibility and minimizing expansion differences by optimal geometrical design and material selection.

An example of typical expansion differences to be taken into account are those between connected HP SHs and RHs. Figure 6 shows snapshots of the time-dependent expansion during a cold start, generated based on dynamic start-up simulation for a 3P RH HRSG (the tube bundles are suspended from the roof; the tubes are 21.3 meter long). This dynamic simulation takes into account the time dependent GT exhaust temperature and mass flow as well as the local heat transfer (exhaust and steam side) and the applied operational control philosophy. As can be seen from Figure 6, a large temperature difference between the tube bundles is visible quickly after heat input. The maximum temperature difference between connecting tube bundles is > 210K (~380°F) (between SH4-SH3 and RH21- RH1), resulting in significant expansion differences.

From the dynamic start-up simulations, the time-dependent expansion of the HP SHs and RHs and the resulting absolute expansion difference between connected HP SHs and RHs is viewed, and in the 3P RH HRSG example a maximum expansion difference of ~70mm (~2.8 inch) is observed, which can be concluded to be significant.

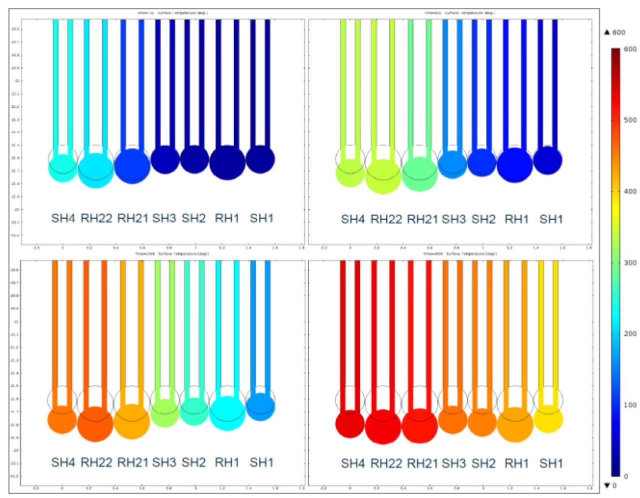

Figure 6*: Expansion (to scale) and temperature (°C) of HP SHs & RHs during a cold start.*

IV. DRUMPLUS™ TECHNOLOGY

DrumPlus is a game-changing alternative to the conventional natural circulation boiler and is therefore suitable for at least the same applications as a conventional natural circulation boiler. The entire set of previous mentioned design challenges haven been tackled. In the DrumPlus-design, the drum diameter is minimized to obtain a smaller drum wall thickness, resulting in reduced thermal stresses. Furthermore, nozzle sizes are minimized and sufficient flexibility is introduced to reduce thermal stress. This is for instance done by application of multiple inside downcomers instead of the typical two outside downcomers.

One of the most important challenges are with the HP drum as this is one of the thickest steel components in the boiler, exposed to thermal stress. In order to minimize the drum size, secondary steam separation in the DrumPlus-design occurs in bottles outside the drum; a smaller holdup time, also referred to as retention time, is allowed and swell is minimized. This is Siemens HTT patented technology and it is shown in a simplified scheme in figure 7, while figure 8 shows the actual insulated HP drum with DrumPlus-technology installed in the El Segundo Power Plant in California, USA. Together, these design features minimize the thermal stresses and thereby make the drum fit for fast starts. In fact, the DrumPlus-design allows for unrestricted GT startup which is unique in large CCPPs.

As an example, table 4 shows a comparison of the total low cycle fatigue damage resulting for a conventional versus a DrumPlus HP drum design, for a fast starting and cycling plant. The results are obtained by dynamic simulation of each type of start-up and shutdown, followed by determination of the time dependent stress profiles with FEM, using the temperatures, pressures and heat transfer coefficients from the dynamic simulations as its input. The time dependent stresses (at the bore of the hole) that result from the FEM simulations are evaluated according the fatigue calculation method of EN 12952-3. Using the calculated fatigue damage per start-stop combination, the total fatigue damage is then determined with the specified number of starts.

The results in table 4 show that the conventional HP drum design does not reach its lifetime for fast start (>100% damage). The lifetime of the DrumPlus drum is about 7 times that of the conventional drum. Having the DrumPlus design means that the HP drum is not limiting the lifetime of the HRSG.

	Total fatigue damage			
	300 cold starts	1500 warm starts	6000 hot starts	Total
Conventional drum: 2280 mm OD 140 mm wall thick.	56%	105%	13%	174%
DrumPlus drum: 1480 mm OD 90 mm wall thick.	9.5%	13%	2.4%	25%

Table 4*: Low cycle fatigue damage for HP drum of a fast starting (~30 MW/min GT ramp rate, F class GT) HRSG having 3 pressure levels and reheat – Conventional versus DrumPlus design.*

DrumPlus™ Technology has been in successful operation in the El Segundo Combined Cycle Power Plant in California, USA. During the first four years of operation, the HRSGs have already started over 1200 times, roughly 600 times per unit and on average about 150 times per year per unit. The units have been proven to safely allow starts with 30MW/minute ramp rates from synchronization to GT full load, without GT load holds and without any issues with swell (i.e. no water dump is required during the fast starts).

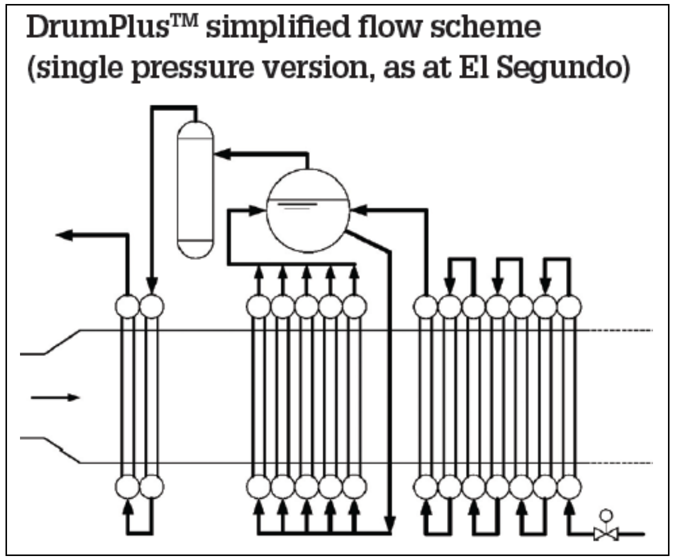

Figure 7*: simplified DrumPlus™ flow scheme*

Furthermore, DrumPlus-technology can easily be applied to other gas turbine frames and HRSG designs. As of May 2018, another nine (9) DrumPlus HRSGs are under construction. Current projects covering Asia, North as well as South America and include a variety of different GT types such as E-class, F-class, and H-class gas turbines. At Lordstown Clean Energy Center in Ohio, USA, two (2) DrumPlus HRSGs – with supplementary firing system - are being installed behind SGT6-8000H GTs of 310 MW power output each (GT output only). The 3 pressure level with reheat HRSGs are designed for ~165 bar (2390 psi) HP pressure.

Figure 8*: insulated HP drum with DrumPlus-technology at El Segundo CCPP, California USA.*

V. THE USER'S BENEFITS

In order to examine the key benefits of fast start using DrumPlus-technology, a fast warm start and a normal warm start are compared in an example calculation. Note that a warm start is typically defined as a start after 8 to 64 hours of standstill. However, instead of standstill time, most important to the HRSG is the amount of heat it still contains. In this example, the HP section of the HRSG is assumed to be at 1 bar and saturated conditions (100°C). With respect to the start-up speed, in this example calculation a fast start is defined as a start with unrestricted GT ramp rate to full load (i.e. no GT load holds) at 30 MW/minute, resulting in expected SCR operation in ~10 minutes after GT ignition. The normal start is defined as a start including a 25 minutes soak time and a 13 MW/minute GT ramp rate to 20% GT load and a 30 MW/minute GT ramp rate above 20% load. In this normal start the SCR is expected to be in operation in ~15 minutes after GT ignition.

This example uses an F-class gas turbine (SGT6-5000F(5) as in the reference plant El Segundo). From the start initiation, the GT reaches full power in only 12 minutes in a fast start, while it takes up to 38 minutes for a normal start. This means that when the CCPP equipped with a fast start HRSG is called upon, it is able to respond 38 – 12 = 26 minutes faster than a traditional CCPP only capable of a normal start. Figure 9 shows the clear difference between the normal and fast start over time by MW gas turbine load. Coming back to the future market requirements with high ramp rates, a similar CCPP as El Segundo consisting of 5 units would be able to reach a ramp rate of 150 MW/minute, while more than 10 traditional units would be needed to reach the same.

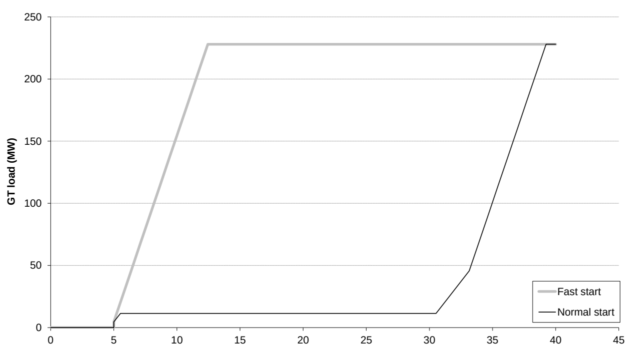

Figure 9*: GT load(MW) build up for a fast and normal start*

i. A quick response to power demand

The ability to respond quickly to fluctuations in power demand is of special importance for so-called spot markets. The CAISO grid operator also operates such a spot market. This is a real-time market which dispatches power plants every 15 and 5 minutes. Prices are established based on supply and demand and power plant operators get paid when supplying electricity to the grid. Fast start versus traditional CCPPs can make much more money by selling more electricity during the start-up phase. During the first forty minutes, 116 MWh can be generated in a fast start - of which 14 MWh already in the 12 minute start-up - while only 20 MWh is achieved with a normal start, outlined in figure 10.

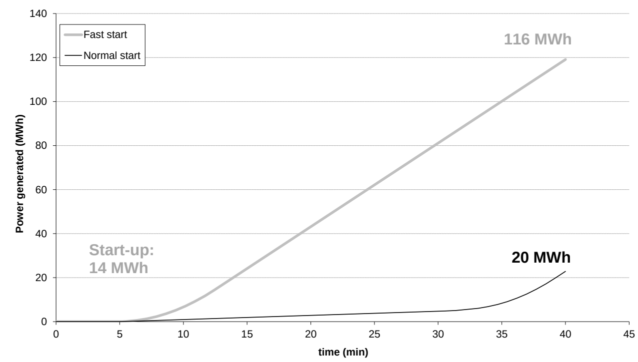

Figure 10*: Cumulative generated power (MWh) for a fast and normal start*

ii. Higher profitability by reduced startup costs

When the GT is ramped up faster to more efficient loads, this reduces the fuel consumption per MWh of electricity produced. Therefore, a fast GT start leads to reduced start-up cost. Note that the fuel consumption is already significant at the moment that the GT starts to deliver load. For example: for a SGT6-5000F, the fuel flow at minimum load (4.5 MW) is 25% of that at full load (228 MW). A normal start would require 9325 kg to bring the GT to full load, while a fast start reaches full load using 3840 kg. When looking at the MWh produced during the first forty (40) minutes, a fast start uses roughly 210 kg per MWh, while a normal start uses about 466 kg per MWh, as illustrated in figure 11.

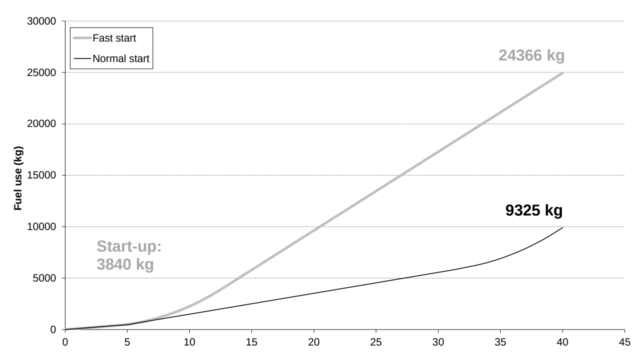

Figure 11*: Cumulative fuel use for a fast and normal start*

iii. Reduced emissions during startup

Both the NOx as well as the CO emissions can be reduced significantly by starting faster. When the GT is ramped up faster, the GT will reach GT loads with low NOx production faster, which reduces the amount of NOx produced by the GT. In addition, the catalyst will warm up quicker, resulting in earlier SCR operation and therefore reduced NOx emissions. As can be seen from figure 12, the cumulative difference between a normal and fast start are significant, with far more electricity produced during the fast start the total amount of NOx emission is estimated at 12 kg during the first 40 minutes of operation, while a normal start emitted 29 kg of NOx in the same time period.

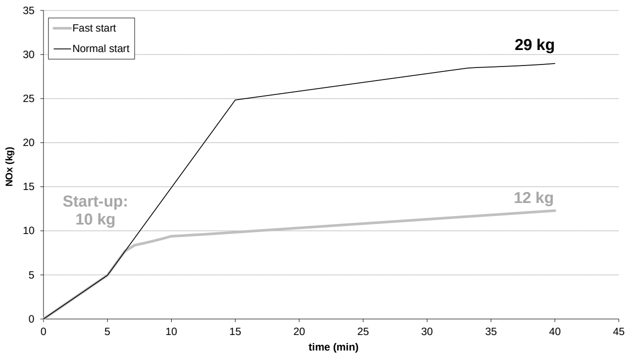

Figure 12*: Cumulative NOx emission for a fast and normal start*

Also CO emissions can be reduced largely. With and without CO catalyst, the total cutback on emissions with a fast start compared to a normal start is impressive. Especially for CO, the startup phase is very important, as can be seen from figure 10. Without the use of a CO catalyst a fast start reduces the relative CO emission compared to a normal start with 12 hours of operation at maximum GT load to only 33% of the total. When using a CO catalyst, a fast startup reduces the CO emissions similarly, with roughly a factor 3 over the period of 12 hours of CCPP operations at maximum GT load.

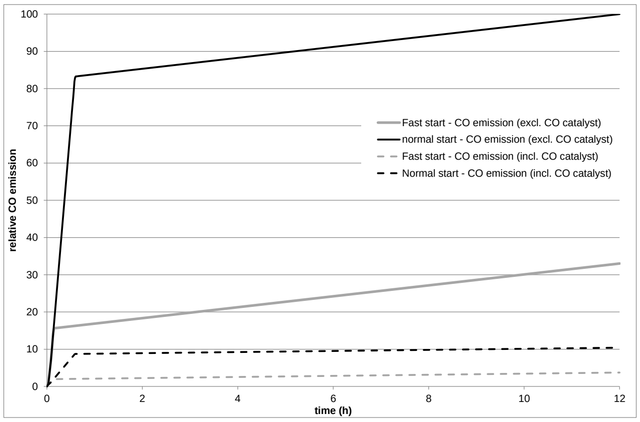

Figure 13*: Total relative CO emission for 12 hours of operation at maximum GT load including fast and normal start*

PREPARING FOR THE FUTURE

Given the extremely changing power markets globally, and the unpredictability of what the future might bring, it is clear that preparing for an uncertain future is key. Based on the current outlook for renewables and the concluding impact on CCPPs, is more than likely that fast start and cycling will play an increasingly important role globally. To prepare for this future, all new CCPPs should be equipped with fast start and cycling HRSG technology like DrumPlus™. It doesn't only bring financial benefits to the operator, but it also significantly reduces the emissions while providing reliable electricity and grid stability.

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