Electric turbo-compounding application to gas engines for power generation in the 1-10 MWe range


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Abstract

Lean-burn spark-ignited gas engines are increasingly being used in power generation to balance wind & solar, lower emissions, increase grid flexibility & stability, and boost electrical and thermal efficiencies. Gas engines from GE have been serving this segment for more than 60 years, recently pushing beyond 24 bar BMEP and 50% electrical efficiency using technologies such as miller cycle technology, two-stage turbocharging and pre-chamber ignition systems. The trends toward a decentralized energy supply and the need to serve both the primary and secondary frequency regulation markets also have led to an increased demand for fast starting, and transient load behaviour.

To make the next leap in performance, much effort has been put into understanding the potential of applying electric turbo-compounding to GE’s Jenbacher* gas engines. This paper examines different simulation and engine test results in the 1-10 MWe range with differing performance objectives. Cases that increase electrical output, electrical efficiency and transient response are discussed and evaluated. The study highlights that although applying turbo-compounding to high BMEP gas engines is indeed challenging, specific opportunities exist to further increase the performance of new and existing fleet gas engines from GE without the need for base engine redesign.

*indicates a trademark of the General Electric Company
Elektrische Turbocompoundanwendungen für statinäre Gasmotoren im Leistungsbereich 1-10Mwe


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Kurzfassung:


*kennzeichnet eine Marke der General Electric Company
1. INTRODUCTION

Gas engines for distributed power generation provide electrical and thermal power in a flexible, efficient and reliable manner. Customers, current trends and legislation all place requirements on gas engine generator sets. These include:

- Low investment costs
- Low operating costs and high availability
- Operational flexibility concerning ambient conditions
- Fuel flexibility (e.g. biogas, sewage gas etc.)
- The ability to provide power on demand with fast start times
- Compliance with current and future emissions legislation

Although customer specifications are impossible to completely anticipate, engine manufacturers can break down the major thermodynamic development targets into:

- High specific power output
- High electrical and thermal efficiencies
- Sufficient distance to knock and misfire limits, together with a low methane number
- Minimum power de-rating due to ambient conditions
- Improved transient behaviour
- Resistance to grid instabilities
- Low pollutant emissions

Historically, GE’s Jenbacher gas engines have been at the forefront of gas engine development, focusing on delivering the above in the 1-10 MWe range. Figure 1.1 shows some of the Jenbacher gas engine milestones and technology steps during the last 60 years, with perhaps the most significant being the combination of miller cycle with high compression ratio pistons, pre-chamber ignition systems and two-stage turbocharging. Figure 1.2 details four of GE’s Jenbacher gas engine offerings between 1 and 10 MWe.
With more than 8,000 engines operating in the field, the proven and reliable Type 3 engine series has been the best-selling Jenbacher product line for nearly 30 years. Operating in the 526 to 1,067 kWe range, the series now offers improved electrical efficiency of more than 41% [1], a development that is available through performance
upgrades to the fleet. Figure 1.3 shows the engine operating space today. Particularly impressive is the engines’ fuel flexibility, with almost 4,000 engines running on landfill and biogas applications.

Figure 1.3: GE’s Jenbacher 3 series gas engine segments

Operating in the 0.8-1.6 MWe range is GE’s Jenbacher Type 4 gas engine series, with more than 2,000 engines delivered worldwide. Like the Type 3, approximately half of the engines operate in combined heat and power (CHP) applications, with the other half serving the landfill and biogas segments. More than 44% electrical efficiency [1] is possible with the Type 4, with more than 90% total efficiency for CHP applications.

The Type 6 engine series, with more than 4,000 engines delivered and running in the field, has operated in the 1.5-4.5 MWe range for almost 30 years. The focus of this series is on CHP and greenhouse applications as per Figure 1.4. The latest Type 6 technology achieves electrical efficiencies up to 47% and BMEP values up to 24.5 bar [2].
Figure 1.4: GE’s Jenbacher 6 series gas engine operating space

The latest offering from GE’s Jenbacher gas engines is the J920 FleXtra, operating between 9.4 and 10.4 MWe with demonstrated electrical efficiencies up to 50% [3] and total efficiencies up to 92% without the use of heat pumps. With more than 32 units sold to date, the engines generally operate in CHP mode in the winter, but switch to peaking services during summer operation.

Improving this already highly powered and efficient portfolio is a special challenge requiring new technologies. Furthermore, in a purely balancing capacity the engines provide flexible, reliable power & efficient power to start fast when the wind doesn’t blow or the sun stops shining. This paper details investigations using 1D simulation and SCE/MCE testing to assess how the turbocharging system, including the addition of an electric turbine (ET), can be modified to further increase power output and electrical efficiency without major base engine redesign or development. This increase in power can be beneficial to cover power plant auxiliary systems that boosts plant output & efficiency. The studies also identified the possibility of dramatically reducing load pickup times without losses in electrical efficiency.
2. MOTIVATION & CHALLENGES

2.1. Governing reserve

GE’s Jenbacher gas engines traditionally are controlled at steady state using a compressor bypass (CBP), which provides a fast method of regulating the manifold charge density to effectively govern the engine power. In recent years, the CBP has been used in combination with a waste gate (WG) at high loads [4].

Figure 2.1 illustrates an example of the maximum ambient/altitude at which a lean burn natural gas engine can run full load. Along the full load line, the turbocharger (TC) is matched to ensure sufficient governing reserve is available to control engine speed or power, allowing for the effects of humidity swings, gas quality fluctuations and engine aging over time. Aging effects, and how they affect governing reserve over time, are understood for each engine platform, including the influences of compressor, turbine and charge air cooler fouling, combustion chamber deposit build-up and valve recession. At lower ambient temperatures and altitudes, the governing reserve increases considerably higher than is required to control the engine. This excess governing reserve normally is achieved by under-sizing the turbine nozzle area, resulting in losses in pumping mean effective pressure (PMEP) and engine efficiency at normal running conditions.

Figure 2.1: Maximum ambient and altitude for a typical lean burn gas engine

An engine simulation performed on a specific Type 4 engine version assessed the entitlement if these governing reserve losses were to be fully recovered for a new engine (i.e., the turbine nozzle area was matched at ISO conditions to the minimum governing reserve required
to control the engine at steady state). In this case, the PMEP and brake thermal efficiency of a typical Type 4 engine could be improved by approximately 500 mbar and 1% respectively. Similar advantages can be seen on each engine platform, but slight variations are seen dependent on the TC match (specific engine aging factors and version altitude/ambient requirements). If a WG is already included in the baseline engine, entitlement is reduced by approximately 0.3% [4].

Many methods are under investigation to recover these pumping losses. The use of a WG is a proven, cost-effective technology that reduces pumping losses and recuperates some of the lost electrical efficiency. However, it still results in lost exhaust enthalpy by bypassing a proportion of the high-pressure exhaust gases around the turbine and venting to the exhaust stack. Other possible methods that recover a much higher proportion of the losses are the use of variable valve trains (variable intake valve closing) [5] or variable geometry turbines. These allow the pumping work to be decreased along with full expansion of the exhaust flow through the TC. However, the development and production costs of introducing such technologies across all engine platforms presents challenges.

The use of an electric turbine (ET) to extract extra power from the exhaust is well documented [6-8], and is another possible solution to recouping a large proportion of the governing reserve. Although specific piece cost is still a challenge, the possibility of adding an ET to the engine – without the need for major base engine redesign or development and perhaps retrofitting in the field – is attractive.

### 2.2. Electric Turbine Concepts

The two main concepts that have been studied in detail are: placing an ET downstream of the engine and placing an ET within the WG line parallel to the turbocharging system. Both concepts have their advantages and disadvantages, as previously documented in a study looking specifically at the J624 [9].

**Figure 2.2** illustrates the concept of placing an ET in parallel to a WG, downstream of the engine. In the following studies, this is relevant to the single-stage turbocharged Jenbacher Type 3, Type 4 and Type 6 engines. The ET, with the aid of power electronics, is used to produce power with the generator by controlling the speed for excellent turbine efficiency. The WG is used to fine-tune the flow around the ET, effectively controlling the power produced by the generator and the
backpressure to the TC. Thus, the WG ensures the power from the ET is maximized, regardless of ambient/altitude/engine aging effects but also serves as a safety device so the ET does not overload in extreme conditions.

Figure 2.2: ET downstream of the turbine on a single-stage engine

Figure 2.3 illustrates the concept in which an ET is placed in parallel to an LP and HP turbine and is relevant to the two-staged turbocharged Type 6 and Type 9 engines from GE's Jenbacher gas engines. The system is controlled in a similar way, with the exhaust flow through and the power produced by the ET controlled using the WG.
It is feasible to further increase the power delivered by the ET by undersizing the turbine-effective area of the engines’ TC. This increases the governing reserve available for the ET, as well as the power the ET produces. This in turn increases the exhaust manifold pressure, which has adverse effects on the engine’s breathing and combustion cycle.

### 2.3. Knocking reserve

The requirements for high specific output and efficiencies for modern lean burn natural gas engines drive the necessity to operate engines close to the knocking border for a given gas quality. This is achieved by optimizing the combustion process for each individual cylinder using real-time cylinder head mounted-pressure transducer or accelerometer data as a feedback. Depending on local gas quality, engine versions usually are trimmed by adjusting piston compression ratio (CR) and/or miller cycle (coarse adjustment) and ignition timing (fine adjustment), so knocking margin is minimized and efficiency maximized on a customer/site-specific basis.

Many factors influence the tendency of end gas knock in spark ignited engines. One relevant to the discussion that follows is the influence of exhaust gas residuals trapped from the previous combustion cycle. The residual exhaust gas has two main effects on the combustion process –
increasing the bulk in cylinder charge temperature and thus the end gas temperature, and acting as free radicals, promoting the chemical reactions that can trigger auto combustion.

As the trapped residual fraction is heavily dependent on the exhaust back pressure at the end of the exhaust stroke, specific care needs to be taken when under-sizing the engine’s turbine area.

A trade-off between the additional electrical power produced by under-sizing the engine’s turbine area must be considered versus the additional PMEP losses and the increased knocking tendency.

2.4. Consideration for under-sizing engine turbine

Tests performed on the Type 6 single-stage and Type 9 two-stage turbocharged engines show a nonlinear influence of under-sizing the turbine on combustion knock. Figure 2.4 indicates that if the scavenging pressure is strongly positive, the influence of changing the scavenging pressure on the methane number (MN) is much smaller than if the scavenging pressure is close to zero or is positive. In fact, for a given change in scavenging pressure, the change in MN for the Type 6 SSTC is approximately three times that of the Type 9 TSTC. Thus, for engines near to the knocking border there is more potential to undersize the turbine to maximize loading on the ET if the scavenging pressure is already strongly positive (i.e., the overall turbocharging efficiency is high).
3. ELECTRIC TURBINE CASE STUDIES

Three case studies were investigated in further detail – a J320 biogas field engine, a J612 single-stage engine, and a J920 two-stage engine operating on natural gas.

3.1. Type 3 biogas

Applying a downstream ET was considered on a J320 biogas field engine due for a 40,000-hr overhaul. It was believed that the potential of applying the ET technology could be maximized, given the knocking margin this specific biogas version has (high MN gas together with low piston CR).

This was compared against the possibility of using the latest performance hardware upgrades, also with and without ET.

Hardware upgrades available to service this specific customer engine included increased piston CR, updated camshaft profiles, improved cylinder head port flow, flow-optimized gas mixer, and improved controls algorithms to balance individual cylinder combustion. Together,
these service options were available to apply to the engine, while keeping the base engine peak firing pressure within limits and maintaining knocking margin throughout the life of the engine (i.e., accounting for in-cylinder deposit formation).

In the cases with ET applied, the on-engine TC nozzle area was minimized, increasing the exhaust manifold pressure until either the peak firing pressure (PFP) limit and/or knock limit was reached (including margin for engine aging). The ET nozzle area was reduced, increasing the back pressure on the engines turbocharger until there was no excess governing reserve at a chosen ambient condition.

Figure 3.1 illustrates the resultant engine performance deltas, assuming the customer runs the engine such that it is always derated (i.e., the biogas plant is at maximum capacity with the gas supply to the engine always less than needed to pull full load so, gas flaring never occurs,).

In this case, the engine hardware service upgrade would increase power output by approximately 3.6%. Furthermore, adding the ET to utilize the governing reserve would increase the total power output approximately 6% versus baseline.

If the ET is added to the baseline engine while under-sizing the engine TC turbine area, the overall power also can be increased by approximately 5.8%. Note that in this case, the increase to exhaust manifold pressure results in an engine power loss of approximately 3.4% due to increased pumping losses and thus reduced engine efficiency. This is compensated by an ET output of approximately 10.2% of the baseline power.

Upgrading the legacy products in the field comes down to a question of economics for the customer. The total power is maximized when applying the ET to the engine, but the ET power contribution is approximately four times greater when applied directly to the baseline engine versus when applied together with the engine performance hardware upgrade. Assuming the ET size and cost are proportional then, as a major overhaul is due in this case, it would make sense to upgrade the engine hardware for maximum efficiency and minimum ET cost.
Figure 3.1: Potential performance improvements for a J320 biogas engine with constant gas consumption.

Figure 3.2 illustrates the resultant engine performance deltas assuming the biogas plant has the capability of varying or increasing gas supply to maximize load. In this case, the picture looks a little different.

The engine service upgrade would significantly decrease fuel consumption (approximately 3.5%). Further adding the ET to utilize the excess governing reserve would increase the total power output by approximately 2.3% versus baseline.

If the ET is added to the baseline engine while under-sizing the engine TC turbine area, the overall power also can be increased by 11% versus baseline. However, the gas consumption also significantly increases and is 8.6% more than that achieved with ET together with the hardware upgrade option.

Again, economics would drive the decision as to which option is best for the customer considering the electricity tariffs and the costs of processing the gas and the size/cost of the ET applied.
3.2. Type 6 single-stage natural gas

Similarly, a study examined the Type 6 single-stage engine running on natural gas. It is assumed all engine versions have been defined to run without excessive knocking margin and, in general, the electrical efficiency is always optimized. Therefore, reducing the turbine area to maximize the power output from the ET will have a significant impact on the combustion process (as per Figure 2.4). It is essential to make base engine hardware changes to maintain knock margin with a given gas quality. For simplicity, only piston changes were considered for this study, as many different CRs already are available in production.

A 1D simulation model was matched to the two Type 6 operating points on the left of Figure 2.4 to give good agreement with the measured PMEP and scavenging pressure. Significantly, the trapped residual mass increased by almost 50% and the end gas temperature increased significantly when switching from positive to negative scavenging pressure. Reducing the CR of the piston by 1 reduced the end gas temperature back toward the baseline.
3.2.1. Type 6 Generator set application

Figure 3.4 shows similar results for the J612 to the J320, with approximately 2.5% extra electrical power produced by the ET at ISO conditions. Electrical efficiency increases by approximately 1.1% (i.e., no increase in fuel consumption).

By under-sizing the engine turbine area, and in parallel reducing the piston CR by 1, it is possible to increase the power output by a further 4.4%. However, the overall electric efficiency increases by only 0.7% in this case, equating to a gas consumption increase of 5.3% versus baseline.

When considering current ET hardware costs and extra gas consumption versus the additional revenue created by the ET electrical power increase, the business case to maximize the power output by reducing turbine area and piston CR is, in general, a difficult one for natural gas generator sets.
3.2.2. Type 6 CHP application

Figure 3.5 demonstrates additional considerations for CHP. The additional electrical power produced by the ET is entirely offset by the loss in thermal power from the exhaust gas. Therefore, unless somehow the electricity tariff for the customer far outweighs the heating tariff, CHP applications make no sense for an ET.
In general, applying an ET to an already well optimized natural gas engine is still a challenge. The business case currently looks best for generator set applications targeting power generation when using the ET to utilize only the excess governing reserve portion. Of course, there are some exceptions to this rule, and the ET should be assessed on a regional and customer-specific basis.

3.2.3. Type 6 transient application

Finally, the technology looks attractive when considering the high electricity tariffs offered for engines capable of serving frequency regulation markets. This leads to increasingly fast transient requirements for the development team.

In Europe, the synchronous grid of Continental Europe (ENTSO-E) [10] must retain the frequency within a tight tolerance around 50 Hz, with both generation and demand in equilibrium. At frequencies below 49.99 and above 50.01 Hz, primary reserve power (so-called spinning reserve) must be activated by the transmission system operator to maintain the frequency between 49.8 and 50.2 Hz (minimum offer is 1 MW), and must be available within 30 seconds for at least 15 minutes. Secondary reserve power (minimum offer is 5 MW) must be available within 5 minutes.

![Figure 3.6: ENTSO-E frequency regulation market classification](image)

In recent years, fast start-up and load ramp rates have become a greater focus for GE and its Jenbacher gas engines. Under-sizing the engines’ turbine is one obvious and successful method to improving transient response. Figure 3.7 illustrates a back-to-back transient test taking the same Type 6 example above with the turbine under-sized. The test was performed with all other boundary conditions held constant, i.e., cold but pre-heated engine (engine shut down...
overnight), and the same calibration settings (e.g., fuelling enrichment). The new hardware configuration resulted in a 40% reduction in load ramp time, together with reduced start-up emissions.

![Graph](image)

**Figure 3.7:** J612 preheated start performance improvement with under-sized turbine

When applying the undersized turbine, reduced compression ratio and ET together, it is possible to achieve these reductions in start-up performance with 6.9% electrical power and 0.7% electrical efficiency improvements displayed in Figure 3.4.

### 3.3. J920 FleXtra two-stage natural gas

One of the main challenges for engines in the 10 MWe space is the ability to serve the primary and secondary frequency markets while also achieving emissions targets as per the regulations for larger power plants. Considering the findings on the Type 6 platform, the opportunity to apply an ET to the J920 FleXtra was also considered.

In the case of the J920 FleXtra, the influence of under-sizing the HP and/or LP turbine area on knocking tendency is much less (Figure 2.4). Thus, it is feasible to perform reductions in nozzle area (scavenging
pressure) without the need to change the baseline engine hardware, requiring only small spark timing adjustments.

A parametric study was performed using 1D simulation to understand the effect different combinations of high pressure and low pressure turbine trim have on full load electrical efficiency and on pre-heated engine start-up time. Figure 3.9 summarizes the findings.

![Figure 3.9: Potential steady state and transient performance improvements for the J920 FleXtra natural gas generator set](image)

Significant reductions in load ramp time can be achieved by under sizing the baseline engine turbine nozzle areas, but at the expense of electrical efficiency (due primarily to increased pumping losses).

In this case, if an ET is sized to use only the governing reserve of the baseline engine, the electrical power and efficiency can be increased by 1.2% and 0.6% respectively, compared with the baseline (less than earlier studies due to the baseline engine employing a WG). This advantage is held through the entire range of turbine adjustments, and it is possible to reduce start-up time significantly without electrical efficiency loss.

If the ET size is further increased, as much as 3% increase in electrical power output is possible versus the baseline engine without loss in electrical efficiency.
4. SUMMARY OF RESULTS

The results of applying an electric turbine (ET) to GE’s Jenbacher gas engines portfolio can be split into two sub categories:

- Extracting electrical power directly from the governing reserve already designed into the engine, requiring no base engine modifications.
  - Dependant on the baseline engine layout, 0.6-1.0% electrical efficiency increase and 1.3-2.5% electrical power increase are possible.

- Under-sizing the on-engine TC turbine area to further increase the governing reserve and thus the electrical power available for the ET. This requires minor base engine changes to maintain knock margin e.g. piston CR and/or spark timing.
  - Dependant on the baseline engine layout and knocking reserve, 0.0-2.0% electrical efficiency increase and 3 – 11% electrical power increase can be realised together with significant reductions in load ramp times.

5. CONCLUSIONS

It has been confirmed that the addition of an electric turbine (ET) further increases the electrical output and efficiency and enables better transient load capability for GE’s Jenbacher engine portfolio in the 1-10MWe range.

The business case to apply ET technology to natural gas generator sets and CHP applications is a challenge. However, the ability to apply the technology without the need for major engine redesign or development makes the technology an attractive one.

Advantages can be seen today when applying ET technology to certain niches, such as:

- Legacy products due for service
- Products with high electrical power tariffs, such as biogas or landfill
- Offsetting losses incurred when modifying a TC turbine area to achieve aggressive load ramps (e.g. potentially required for primary reserve power applications)

Opportunities to apply the technology will continue to grow as the specific piece costs of the ET come down over time.
### 6. ABBREVIATIONS

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<tr>
<th>Abbreviation</th>
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<tr>
<td>BMEP</td>
<td>Brake mean effective pressure</td>
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<tr>
<td>CBP</td>
<td>Compressor bypass valve</td>
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<td>CHP</td>
<td>Combined heat and power</td>
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<td>CR</td>
<td>Compression ratio</td>
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<td>ENTSO-E</td>
<td>European Network of Transmission Operators for Electricity</td>
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<tr>
<td>ET</td>
<td>Electric turbine</td>
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<tr>
<td>HP</td>
<td>High pressure</td>
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<td>LP</td>
<td>Low pressure</td>
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<tr>
<td>MCE</td>
<td>Multi cylinder engine</td>
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<tr>
<td>MN</td>
<td>Methane number</td>
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<tr>
<td>PFP</td>
<td>Peak firing pressure</td>
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<tr>
<td>PMEP</td>
<td>Pumping mean Effective Pressure</td>
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<tr>
<td>SCE</td>
<td>Single cylinder engine</td>
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<td>SSTC</td>
<td>Single-stage turbo charging</td>
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<td>TC</td>
<td>Turbocharger</td>
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<td>TSTC</td>
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7. REFERENCES


