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DEVELOPMENT

# Boosting the Future with IHI

## Evaluating state-of-the-art TGDI Turbo Concepts

IHI CHARGING SYSTEMS INTERNATIONAL

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# Electric Turbocharger Concept for Highly Efficient Internal Combustion Engines

IHI has developed an electrified charging system that further enhances the potential of gasoline engines with Miller timing. The high charging efficiency is based on a fixed geometry turbine without additional control components.

## HIGHER CHARGING REQUIREMENTS

As of today, and for the foreseeable future, Internal Combustion Engines (ICE) are the most utilized powertrain propulsion system and will maintain their key role in the powertrain mix. However, meeting future $CO_2$ and emission targets while improving powertrain dynamics remains a challenge and will require fundamental changes and advanced technologies. One effective, yet comparatively simple and cost-effective method has proven to be the

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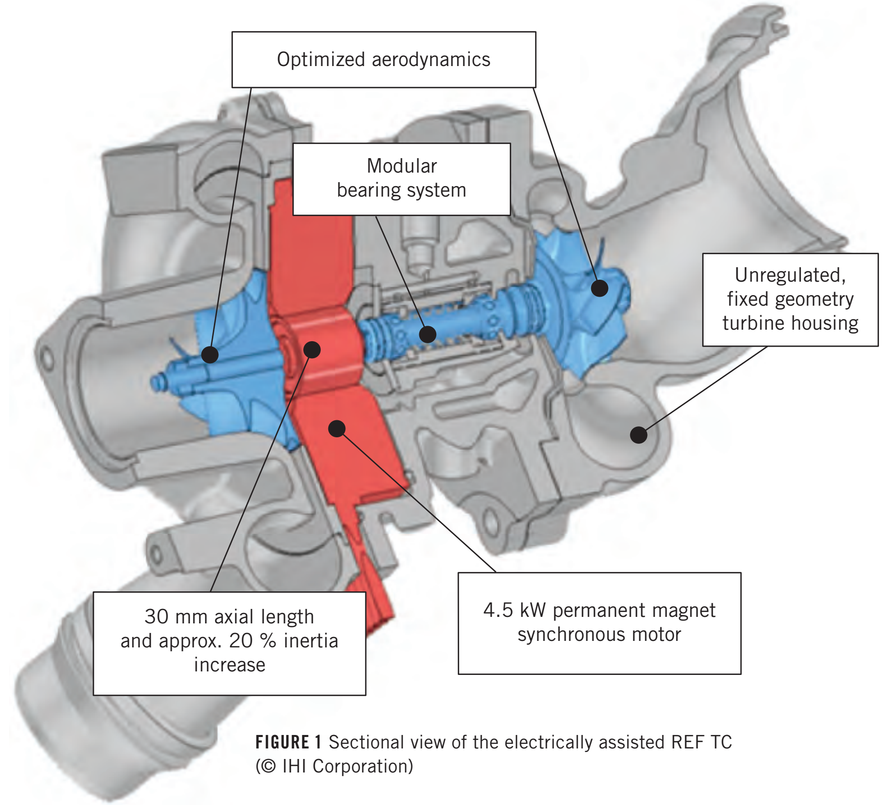



**FIGURE 1** Sectional view of the electrically assisted REF TC (© IHI Corporation)

Miller cycle – a term here denoting both early- and late-inlet valve closing. One consequence of the Miller cycle is the deterioration of the engine's volumetric efficiency which, assuming constant engine power output, must be compensated by the charging system providing increased charge air pressure. Conventional Wastegate (WG) Turbochargers (TCs) are limited in low-end performance and, therefore, penalized in the trade-off between rated power and low end torque. Charging systems with variable turbine technology (also called Variable Geometry System, VGS) can mitigate this conflict, yet are technically challenging and complex in installation and assembly. VGS performance is also limited since a wide-range operation is mandatory [1, 2]. Increasing powertrain electrification carries great potential for further mitigating the conflict between transient, low-end steady state and rated power requirements of the engine. In this regard, electrification can be utilized to improve engine efficiency by employing simple, yet aero- and thermodynamically optimized charging systems. The IHI e-xR concept is targeting hybrid powertrains with highly efficient Miller gasoline engines.

## ELECTRIC CHARGING CONCEPT

The concept features an unregulated, electrically assisted TC, designated as REF for IHI, aiming for maximized aerodynamic efficiency of proven conventional charging system components [1]. Engine efficiency improvements are achieved by exploiting the synergy of Miller cycle thermodynamics with best TC sizing, while transient requirements can be fulfilled by means of TC electrification. The charging concept enables aggressive Miller cycles with increased engine compression ratios while accommodating a large capacity turbine supported by the REF charging system's electric assistance. By deteriorating and fine-tuning of the engine volumetric efficiency via Miller timing, an increased boost pressure requirement leads to an enhanced compressor power demand which in turn needs to be met by the turbine power generated under unregulated conditions. The electrical components of the REF TC are placed between the modular bearing system and the compressor wheel, offering thermal separation from the hot turbine side and simple assembly in mass production. The principal design is shown in **FIGURE 1**.

In this new concept, conventional turbine load control is absent. Possible load control strategies are classic throttle valve and/or inlet valve profile variabilities. Load control is, to some extent, also possible by employing the recuperation capability of the electric system which, in turn, has an impact on the vehicle electric energy management. One attractive alternative is external cooled Low-pressure Exhaust Gas Recirculation (LP-EGR). As is shown later,

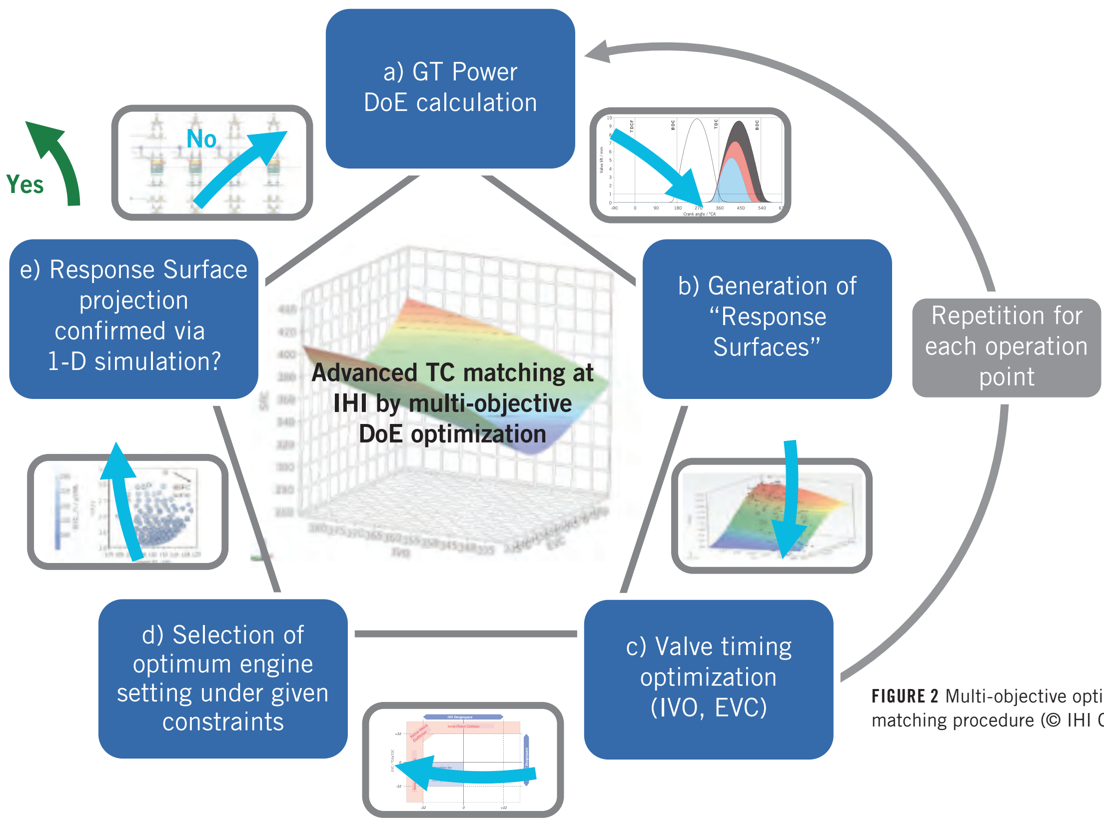
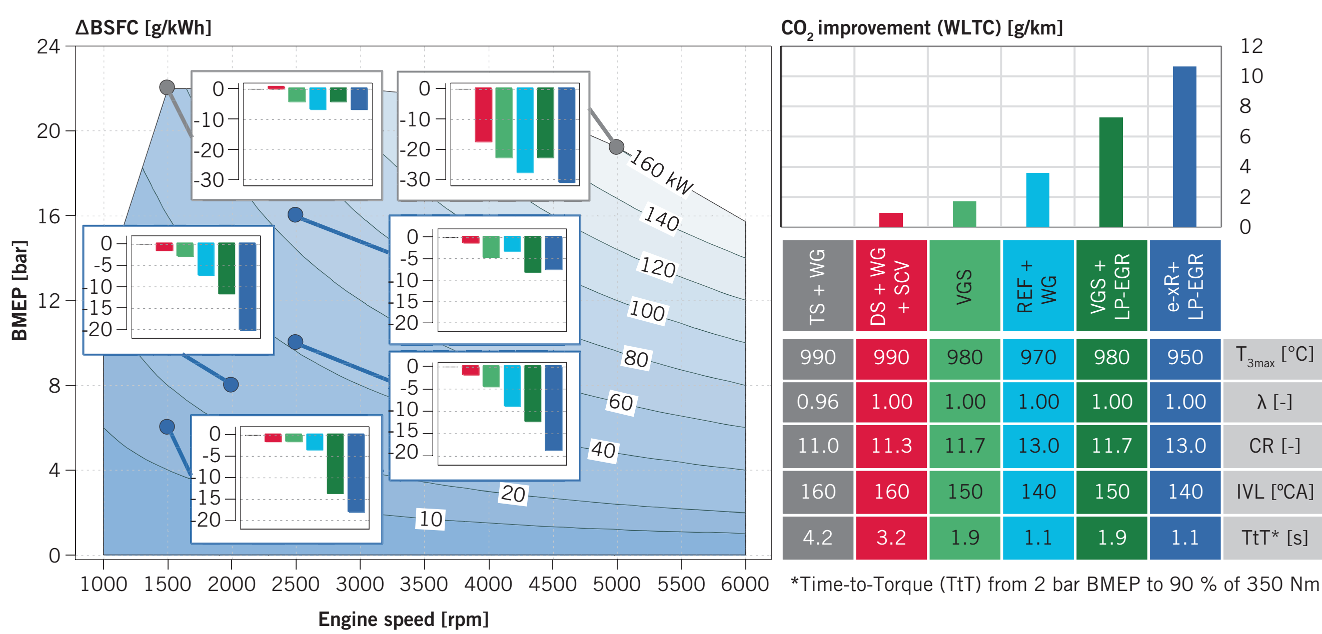



**FIGURE 2** Multi-objective optimization matching procedure (© IHI Corporation)

combining external EGR, Miller cycles with high compression ratios and an REF TC forms the basis of the IHI e-xR concept with significantly reduced real driving emissions. The combination of LP-EGR with the concept of electrically assisted charging is therefore ideal, but not mandatory. The technical challenges are particularly great in vehicles where high demands are placed on the dynamics of the internal combustion engine.

## METHODOLOGY

To quantify potential e-xR concept benefits, a comparison of various state-of-the-art charging systems under equal boundary conditions and constraints




| | TS + WG | DS + WG + SCV | VGS | REF + WG | VGS + LP-EGR | e-xR+ LP-EGR |
|---|---|---|---|---|---|---|
| $T_{3max}$ [°C] | 990 | 990 | 980 | 970 | 980 | 950 |
| λ [-] | 0.96 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| CR [-] | 11.0 | 11.3 | 11.7 | 13.0 | 11.7 | 13.0 |
| IVL [°CA] | 160 | 160 | 150 | 140 | 150 | 140 |
| TtT* [s] | 4.2 | 3.2 | 1.9 | 1.1 | 1.9 | 1.1 |

*Time-to-Torque (TtT) from 2 bar BMEP to 90 % of 350 Nm

**FIGURE 3** Results of ΔBSFC and $CO_2$ reduction in the WLTC and optimized engine parameters (© IHI Corporation)

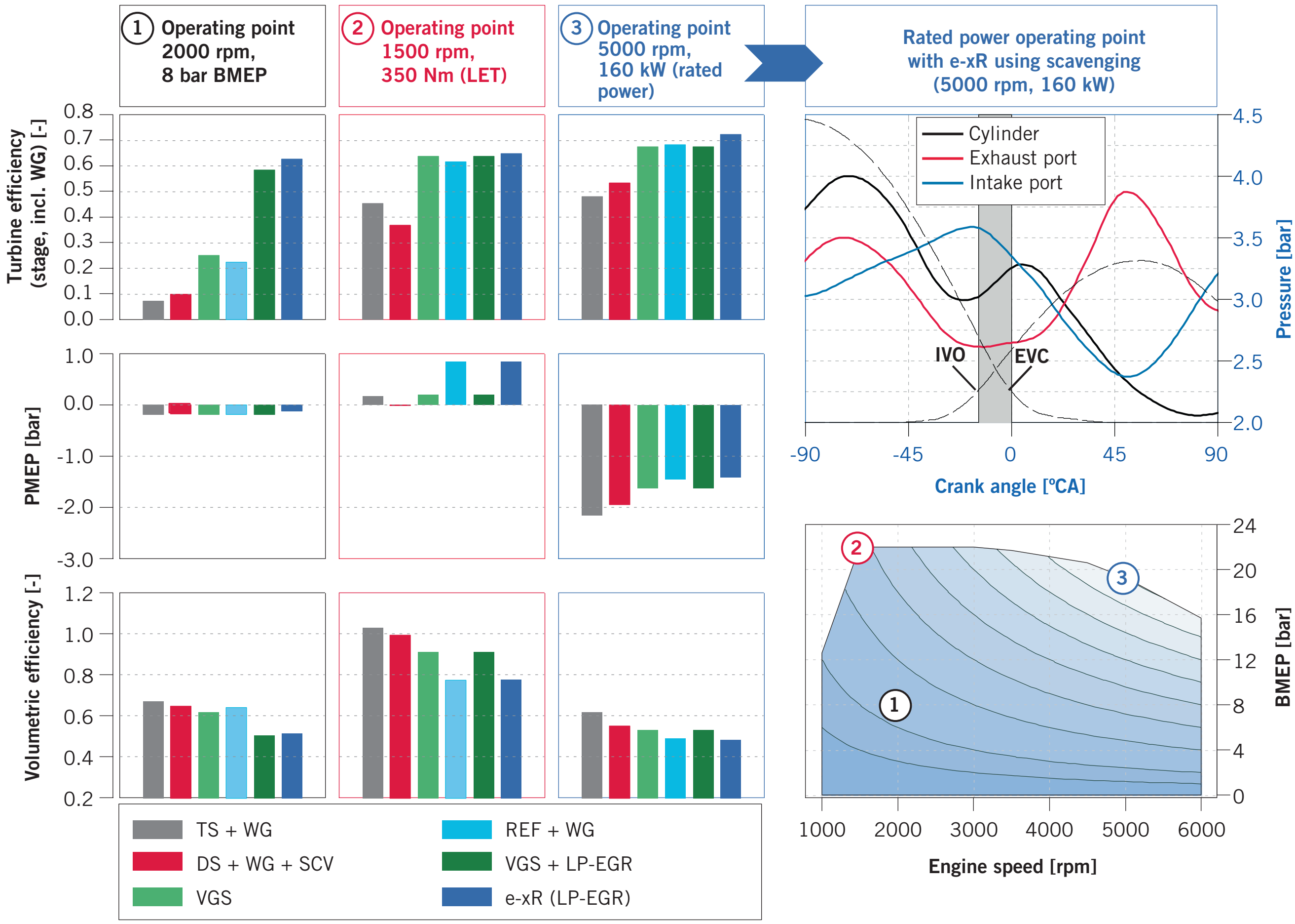



**FIGURE 4** Engine gas exchange parameters (© IHI Corporation)

is presented. Matching calculations are performed using IHI's multi-objective Design of Experiments (DoE) optimization methodology, illustrated in **FIGURE 2**. Multiple 1-D gas exchange DoE simulations by GT Power, **FIGURE 2** (a), produce input for generating so-called Response Surfaces with an external optimization tool of various engine parameters as functions of Inlet Valve opening Length (IVL), Exhaust Valve opening Length (EVL), Compression Ratio (CR), intake and exhaust valve timing and TC sizing, **FIGURE 2** (b). Based on these Response Surfaces, the tool optimizes inlet and exhaust valve timings (Inlet Valve Opening (IVO) and Exhaust Valve Closing (EVC)) for specific parameter combinations of IVL, EVL, CR and TC size, **FIGURE 2** (c). This process is repeated for a number of relevant operating conditions (for example Low End Torque (LET), peak power, part load) to enable the best compromise of IVL, EVL and CR, **FIGURE 2** (d). All investigated charging systems are optimized with this methodology.

Other measures towards $CO_2$ consumption reduction in the Worldwide harmonized Light Duty Test Cycle (WLTC), such as increased hybridization or powertrain downspeeding, were not considered in order to simplify the thermodynamic comparison. The studied base engine is a 2-l four-cylinder gasoline engine with direct injection and a specific power of 80 kW/l. The performance is set to 350 Nm at 1500 rpm and 160 kW at 5000 rpm. The considered vehicle is an E-segment passenger car with a $CO_2$ consumption of 152 g/km in the WLTC. The $CO_2$ reduction is approximated by steady state simulation of relevant points featuring a high work share during the WLTC. All variants are optimized for maximum Miller level, namely with different combinations of IVL, EVL, CR and TC sizes for fixed constraints, to maximize engine efficiency and consequently minimize $CO_2$ cycle consumption, while targeting a Time to Torque (TtT) of 2 s or less from 2 bar BMEP to 90 % of the maximum torque. Constraints include the maximum allowable turbocharger speed, the compressor outlet temperature (maximum 190 °C), a trapping ratio > 0.97 for all operating conditions, a maximum LP-EGR rate of 30 %, as well as the target power. Valve timings are constrained to prevent collisions between the valves or the valves and the pistons.

The TC solutions include a Twin Scroll (TS) turbine with conventional WG, a Double Scroll (DS) turbine with WG and Scroll Connection Valve (SCV), a high-efficiency VGS turbine and a WG REF system. The advanced e-xR concept has full-map LP-EGR load control. The VGS option, being the main competing technology in the examined market segment, is also investigated with LP-EGR to enable fair conclusions.

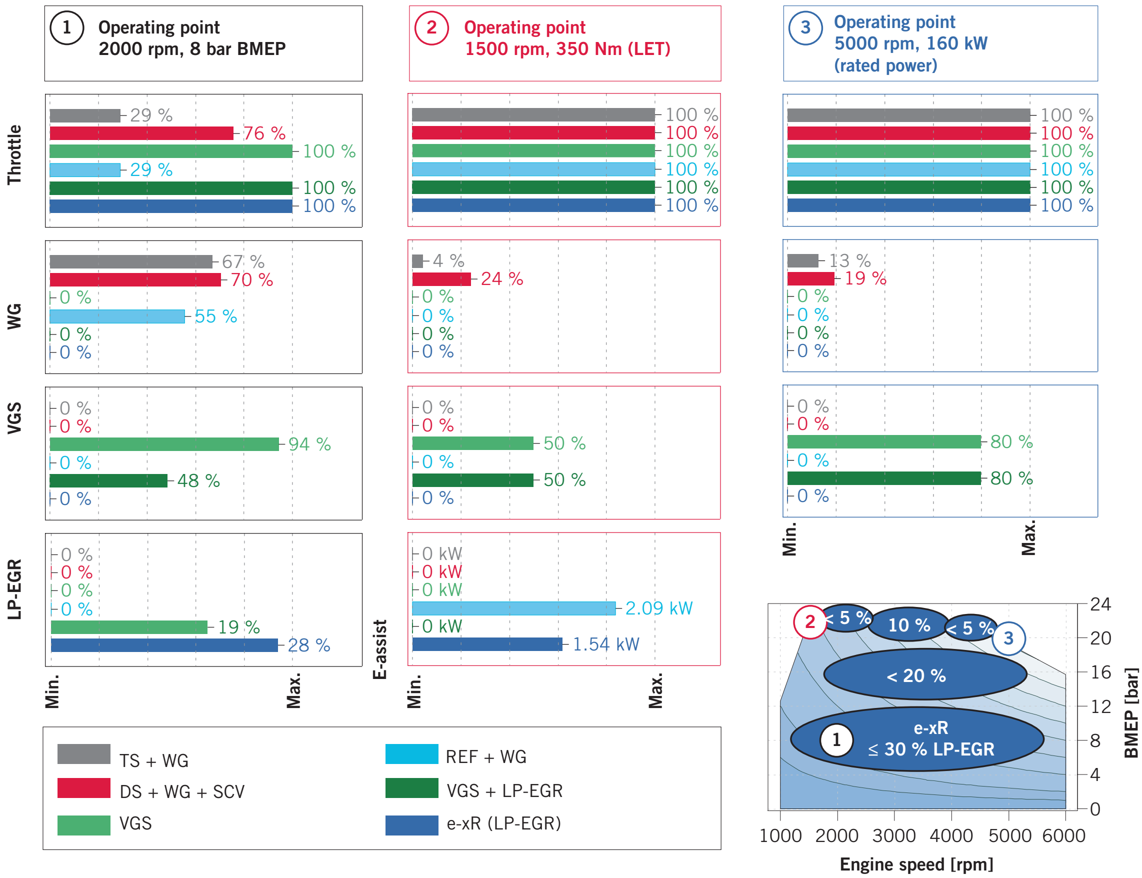



**FIGURE 5** Engine control parameters and e-xR LP-EGR rates (© IHI Corporation)

## RESULTS

Brake Specific Fuel Consumption (BSFC) improvements for relevant operating conditions and expected reductions of $CO_2$ in the WLTC are shown in **FIGURE 3**.

As can be seen, different charging systems allow different levels of Miller timing and, hence, different BSFC reductions. Compared to the baseline TS TC, the DS design with SCV can improve cycle consumption by about 1 g/km as a result of the slightly increased compression ratio. By introducing the VGS, the Miller-specific parameters are improved to feature a shorter IVL (150 °CA at 1 mm lift) and a further increased compression ratio, resulting in a cycle improvement of 2 g/km compared to the baseline. With the REF, the optimizer can afford to neglect transient behavior to some extent, resulting in further improvement. Now the compressor limits the system, with both the prescribed compressor-out temperature limit and the maximum TC speed fully exploited. The resulting $CO_2$ benefit is 3.6 g/km while TtT is improved by 74 %. Subsequently, LP-EGR is examined both for the VGS and the e-xR concept. For the VGS case, the EGR rate is optimized for specific fuel consumption minimization in each operation point, thus leading to EGR rates of up to 20 %. Higher EGR rates show no improvement due to a worsened gas exchange (Pumping Mean Effective Pressure, PMEP) offsetting any EGR benefits, a result of the limited turbine efficiency of the more closed VGS positions necessary to drive higher EGR rates. However, the $CO_2$ cycle consumption can still be improved by 5.5 g/km compared to the VGS without LP-EGR. The e-xR full load efficiency can be maximized by its fixed geometry turbine, hence also improving engine PMEP in part load operation. No EGR rate optimum was found, leading to the maximum allowed value of 30 % and a corresponding improvement of 9 g/km in the WLTC, a > 3 g/km benefit compared to VGS + LP-EGR. The volumetric efficiency reduction to < 0.5 for the REF in the e-xR configuration, associated with the increased Miller parameters, leads to an increased boost pressure demand of > 3.3 bar at the intake manifold. Due to the high turbine efficiency and the non-wasting approach, the pressure before turbine is kept below the level of conventional WG TCs. Thus, for the e-xR the backpressure $p_3$ can be kept at 3.1 bar, even assuming a gasoline particle filter. This yields cylinder scavenging potential even at rated power whereby the Miller level had to be lowered by IVO retardation to exclude trapping ratios < 0.97. This is depicted in **FIGURE 4** which shows engine PMEP, turbine and volumetric efficiency of the investigated systems.

One crucial point of the electrified charging systems is the energy demand during a cycle. The REF, as well as the e-xR concept, allow operation without electrical assisting in all cycle-relevant conditions. Electrical assisting occurs only in the high load LET area (1000 to 2000 rpm) with up to 2 kW of mechanical power. For both electrified charging systems, the Miller parameters, together with the turbine size, were optimized

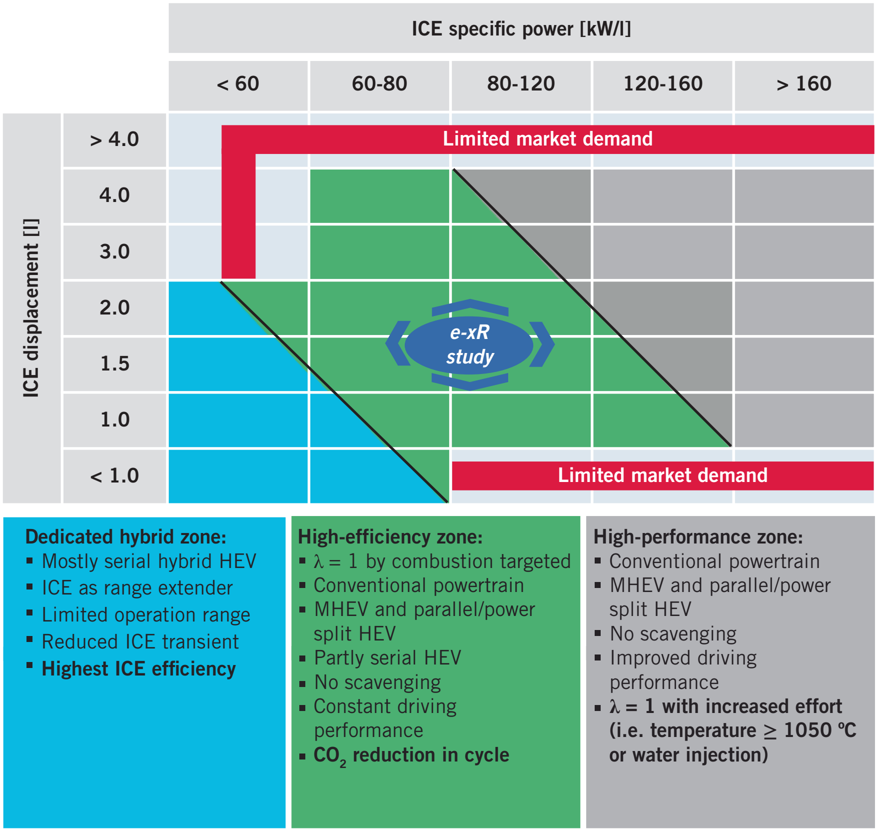



**FIGURE 6** Turbocharged gasoline engine market segmentation (© IHI Corporation)

to fully eliminate WG at rated power. Hence, the required turbine stage sizing is larger than for a conventionally-sized TC. The resulting wheel diameters for both the compressor (tip) and the turbine (shroud) are very similar. The large-capacity REF turbine stage offers 80 % of the VGS maximum flow capacity. More details about the engine control strategy of each system are given in **FIGURE 5**, which shows an overview of relevant engine control parameters for three representative operating points.

Electrified systems require exhaust energy controlling at full load (2500 to 4500 rpm), as uncontrolled operation is limited by the given constraints. The WG REF exhibits a WG bypass of about 5 %, while the e-xR requires LP-EGR rates of up to 10 %.

## SUMMARY


Promising results were shown, with strong benefits in terms of Specific Fuel Consumption (SFC) for the e-xR concept in the 80 kW/l market segment. Still, the concept is suitable for a much larger market range. This requires customized charging systems, but the shown optimization procedure can be utilized to define those. The basic idea of simplifying the electrified turbocharger, thereby maximizing aerodynamic efficiency, can support $CO_2$ reduction in all market segments. A related market breakdown with an indicative ICE requirement overview per segment is shown in **FIGURE 6**.

The presented e-xR concept from IHI is challenging in terms of TC component sizing, electric system demands and aggressive Miller parameters, as well as dynamic LP-EGR load control. The study shows the large SFC improvement potential and how ICE concepts with electrified charging systems are a subject for further elaboration [3]. Electrification is indeed expected to have substantial market share in future gasoline engine boosting concepts, particularly as alternative technology combinations and engine control methods offer additional degrees of freedom for tailoring TCs for the demands of most efficient engines.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