Discover the Alternative to Batteries and Hydrogen-Fueled Power Generation: The Closed Strayton Quad Generator

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Executive Summary

To address the aggressive climate goals that have been set for the next few decades, key segments of the economy, including the maritime and aerospace sectors, are increasingly turning away from the use of fossil fuels and toward designs based on electrical power generation. At the same time, industry leaders are increasingly recognizing that, even if their most optimistic projections for performance advancements in batteries and fuel cells are realized, these technologies are unlikely to perform well enough to help them meet those goals.

Similarly, hydrogen-fueled open-cycle engine options still have a negative impact on air quality. Even more significantly, the incompatibility of hydrogen with our existing fossil fuel infrastructure (from production facilities and storage tanks to delivery equipment and power-generating equipment) also makes widespread adoption of hydrogen-powered equipment unrealistic. In short, attempting to protect the climate with battery- and hydrogen-based technologies reduces performance and increases costs. Our economic and national security will depend on finding ways to protect the climate cost-effectively without reducing productivity, performance, reliability, or safety.

This white paper introduces the Closed Strayton Quad Generator technology, a patent-pending, multifuel, sealed generator design that offers a technically and economically viable alternative to batteries and hydrogen-fueled power generation technologies. It addresses the need for clean, quiet, efficient, compact, multifuel power generation without compromising on performance, climate, cost, and reliability metrics. Even more important, this technology is compatible with today's infrastructure. Recent studies suggest it is potentially cleaner than a hydrogen economy when it is combined with the use of flameless oxidized power to liquid (PtL) synthetic fuels, which this technology makes possible.

This new power generation technology offers the advantage of compatibility with a wide range of fuels, which would allow for a seamless transition from fossil fuels to future net-zero synthetic fuels, while improving performance and reducing costs. All current infrastructure and vehicle assets

remain compatible while the economy adopts this new zero climate impact (ZCI), high-performing generator technology as an alternative to batteries and hydrogen-fueled technologies.

In summary, the combination of PtL and the Closed Strayton Quad Generator technology will make it unnecessary to disrupt the world's economy to protect the climate.

The Concept Underlying Closed Strayton Quad Generator Technology

The Closed Strayton Quad Generator (CSQG) links an external heat source (nuclear, solar, or combustion) with a sealed heat engine that combines a Brayton cycle with an acoustic Stirling cycle to create a Strayton (Stirling + Brayton) thermodynamic cycle (Figure 1). The CSQG cycle has an overall higher system efficiency, specific power, and reliability than each individual Brayton and Stirling cycle can achieve separately. The integration is achieved by installing an acoustic Stirling heat exchanger pair in the hollow rotating shaft of a Brayton cycle generator to provide both Brayton turbine conductive cooling and Brayton thermal recuperation. Such a cycle can operate anywhere, using any heat source, while achieving significant new performance metrics.

The Brayton cycle waste heat acts as a topping cycle, delivering thermal energy to the shaft-embedded acoustic Stirling cycle. The four Strayton cycles are combined into a quad configuration to facilitate interstage cooling and reheating, and to complete a full acoustic wavelength 360° acoustic loop for significantly increased Stirling power, Brayton internal

What Are Power-to-Liquid (PtL) Synthetic Fuels?

PtL fuels, which were first developed early in the twentieth century, are synthetically produced liquid hydrocarbons. In the 1920s, chemists Franz Fischer and Hans Tropsch began work on an indirect way to liquefy coal, in which solid coal was first transformed into a gas. The process they developed, which is still one of the techniques used to produce PtL fuels today, involves introducing metal catalysts at 150 to 300 °C (302 to 572 °F) to set off a variety of chemical reactions that produce liquid hydrocarbons.

Today, renewable electricity has replaced coal as the key energy source used in the process, and water and carbon dioxide (CO_2) are the main resources used in PtL production:

- Step 1—Renewable energy powers electrolyzers (devices that use electric current to split water molecules into hydrogen and oxygen gases) to produce green hydrogen.
- Step 2—Climate-neutral CO_2, captured through various methods including Direct Air Carbon Capture, is converted into carbon feedstock.
- Step 3—Carbon feedstocks are synthesized with green hydrogen to generate liquid hydrocarbons using the Fischer–Tropsch process or similar methods. The hydrocarbons are then converted to produce a synthetic equivalent to kerosene.

recuperation, and Brayton turbine cooling with a single recuperator, inter-cooling, and reheating. The purpose of this arrangement is twofold. First, the compressor interstage cooling and the turbine inlet reheating at all four stages improves the Brayton cycle efficiency and only requires a single recuperator. Second, the hollow rotating shafts of all four Brayton generators have an acoustic Stirling engine inside and the quad configuration enables the four regenerators to be located acoustically one-quarter wavelength apart. This is like earlier multistage Stirling engines that used pistons that oscillated with a 90° phase angle difference, but rather than using oscillating pistons, each acoustic Stirling engine is located acoustically 90° apart to achieve the same higher specific power acoustic Stirling cycle, but without the complication of mechanical linkages. The high-power acoustic power loop provides turbine cooling, Brayton bottoming cycle, combustor bottoming cycle, or inter-cooling bottoming cycle. It also provides acoustic cooling power for other powertrain components.

Each quad layer has an acoustic Stirling loop with four no-moving-parts acoustic engines; the middle layer also has the four rotating Brayton engines. In total, 16 engines are combined synergistically. The only moving parts are the four Brayton shafts and the three bidirectional turbine acoustic generators, which are supported by no-contact gas bearings that do not require maintenance or have a life-limiting mechanism. Due to the CSQG's hermetically sealed working fluid, it is aircraft-type and flight-speed independent because the working fluid is pressurized and is environment independent. It also allows the postcombustion emissions to be fully managed to provide essentially zero greenhouse gas emission because exhaust gases are routed through a low-speed muffler rather than being directly inserted into the jet for propulsion.

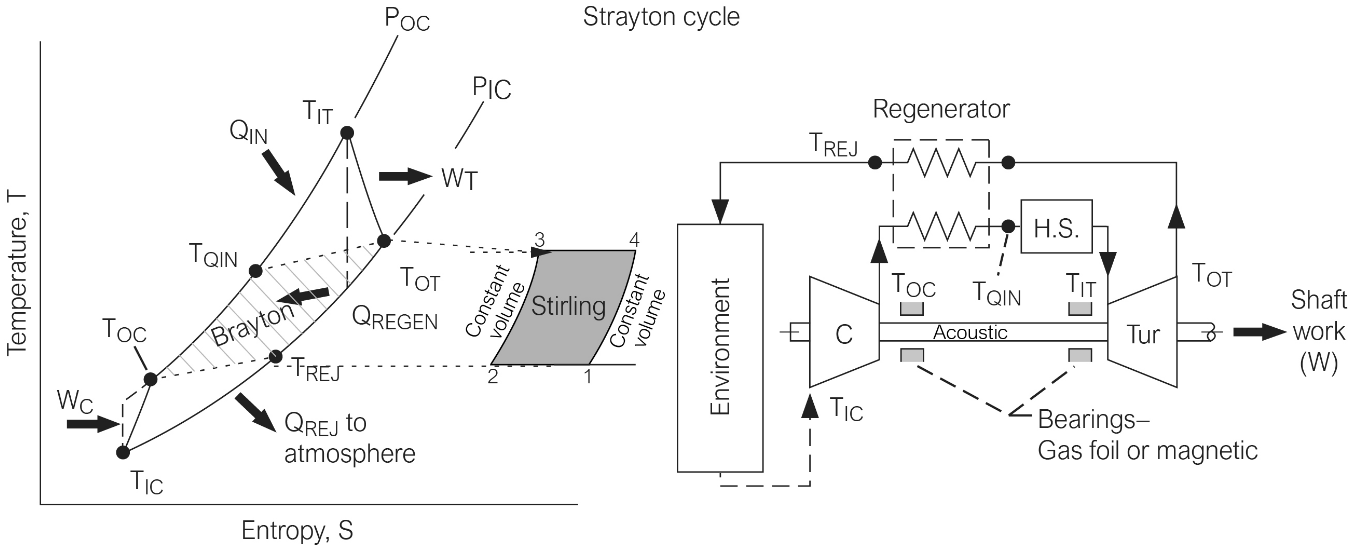


Figure 1.—The Strayton (Stirling + Brayton) thermodynamic cycle, temperature (T) versus entropy (S). C: Compressor; H.S.: Heat source; P_{IC}: Pressure of flow into compressor; P_{OC}: Pressure out of compressor; Q_{IN}: Heat energy into engine; Q_{REGEN}: Heat transferred in the recuperator; Q_{REJ}: Heat energy rejected out of engine; T: Turbine; T_{IC}: Temperature of flow into compressor; T_{IT}: Turbine inlet temperature; T_{OC}: Temperature of flow out of the compressor; T_{OT}: Temperature of flow out of the turbine; T_{QIN}: Temperature of the heat into the engine; T_{REJ}: Temperature of heat rejected from engine; W_C: Work required for the compressor; and W_T: Work produced by the turbine.

Note that in both the nuclear (Figure 2) and combustion (Figure 3) designs, the heat source is located external to the sealed engine. External combustion heating of a closed cycle allows for clean, flameless oxidation (FLOX), exhaust dehumidification, and catalytic reduction, as shown in Figure 4. That makes it possible to achieve ZCI with future synthetic fuels without sacrificing compatibility with today's fuels and infrastructure.

As the combustion chart in Figure 4 indicates, flameless oxidation is usually very difficult to implement inside an engine due to both internal flow conditions and geometry constraints. Although these constraints are removed with closed cycles, a different constraint arises. In a closed cycle, the turbine inlet is normally limited to temperatures lower than 1,200 K because a closed system cannot cool the turbine with outside air, as is commonly done in open-cycle turbofans. As shown in Figure 5, ZCI flameless combustion conditions require turbine inlet temperatures higher than 1,500 K.

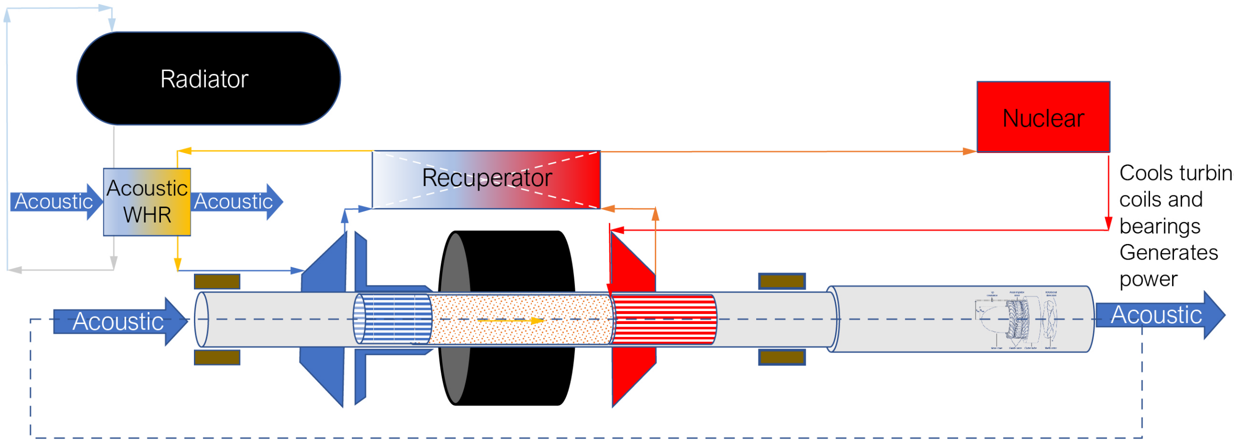


Figure 2.—CSQG with nuclear heat sources.

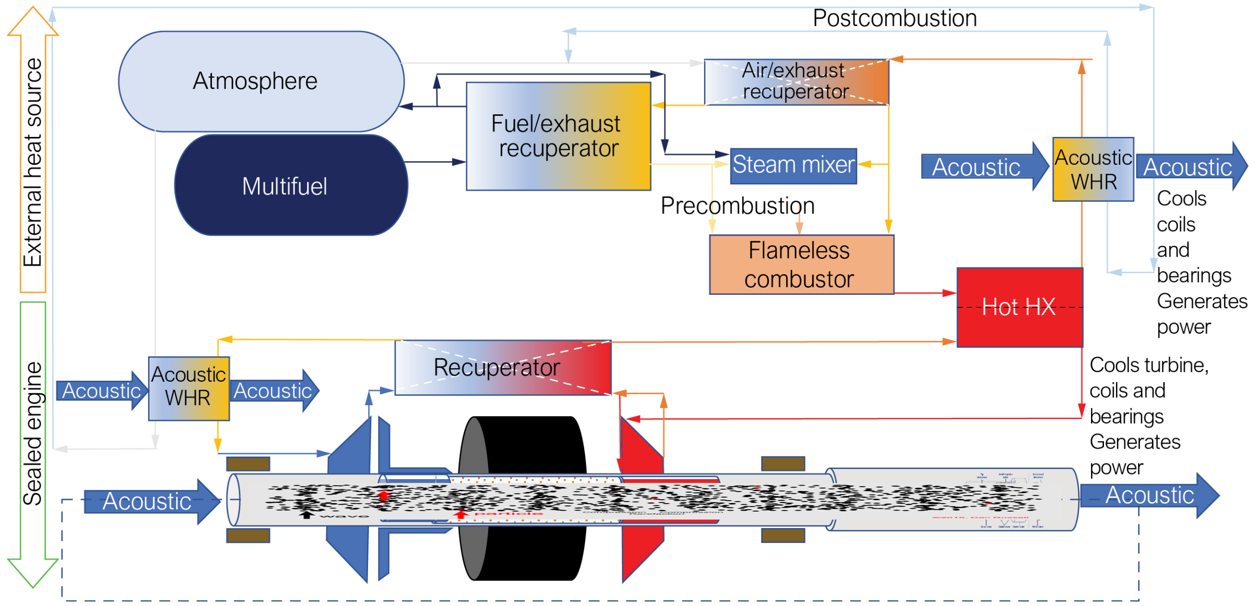
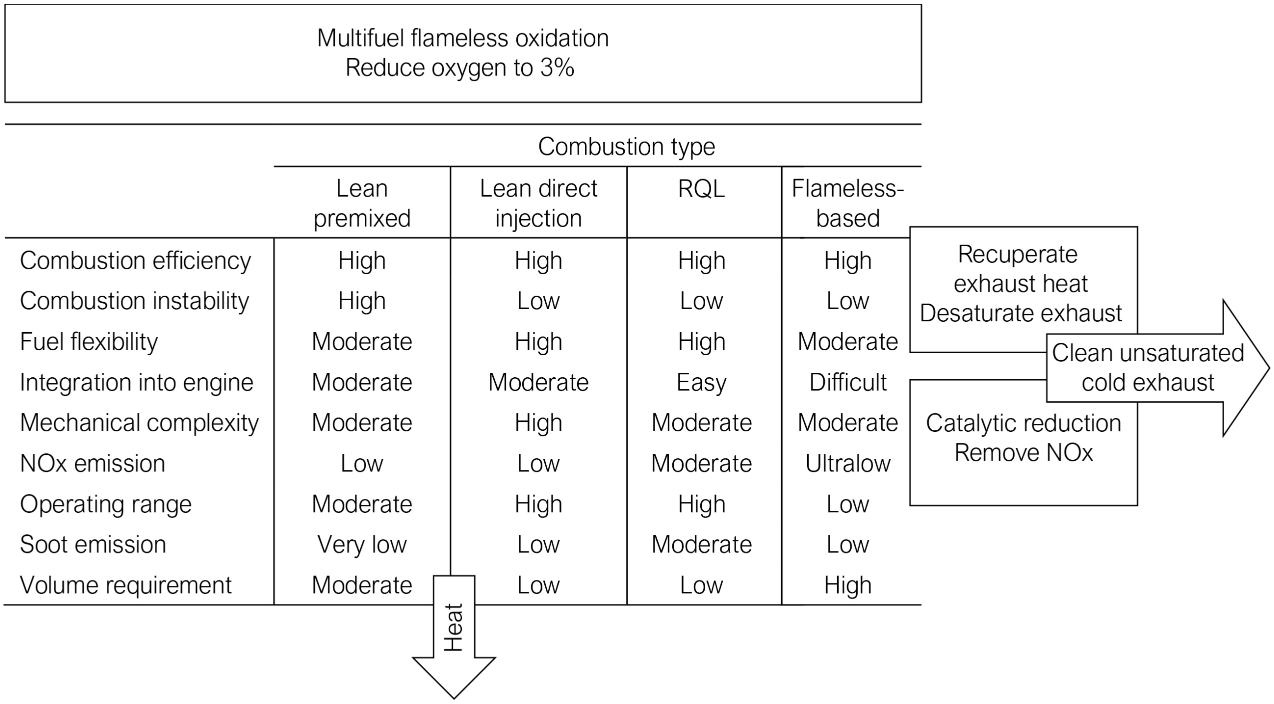


Figure 3.—CSQG with combustion heat source (Ref. 1).



	Combustion type			
	Lean premixed	Lean direct injection	RQL	Flameless-based
Combustion efficiency	High	High	High	High
Combustion instability	High	Low	Low	Low
Fuel flexibility	Moderate	High	High	Moderate
Integration into engine	Moderate	Moderate	Easy	Difficult
Mechanical complexity	Moderate	High	Moderate	Moderate
NOx emission	Low	Low	Moderate	Ultralow
Operating range	Moderate	High	High	Low
Soot emission	Very low	Low	Moderate	Low
Volume requirement	Moderate	Low	Low	High

Figure 4.—Infrastructure-compatible synthetic fuels can have net-ZCI with external combustion (Ref. 2).

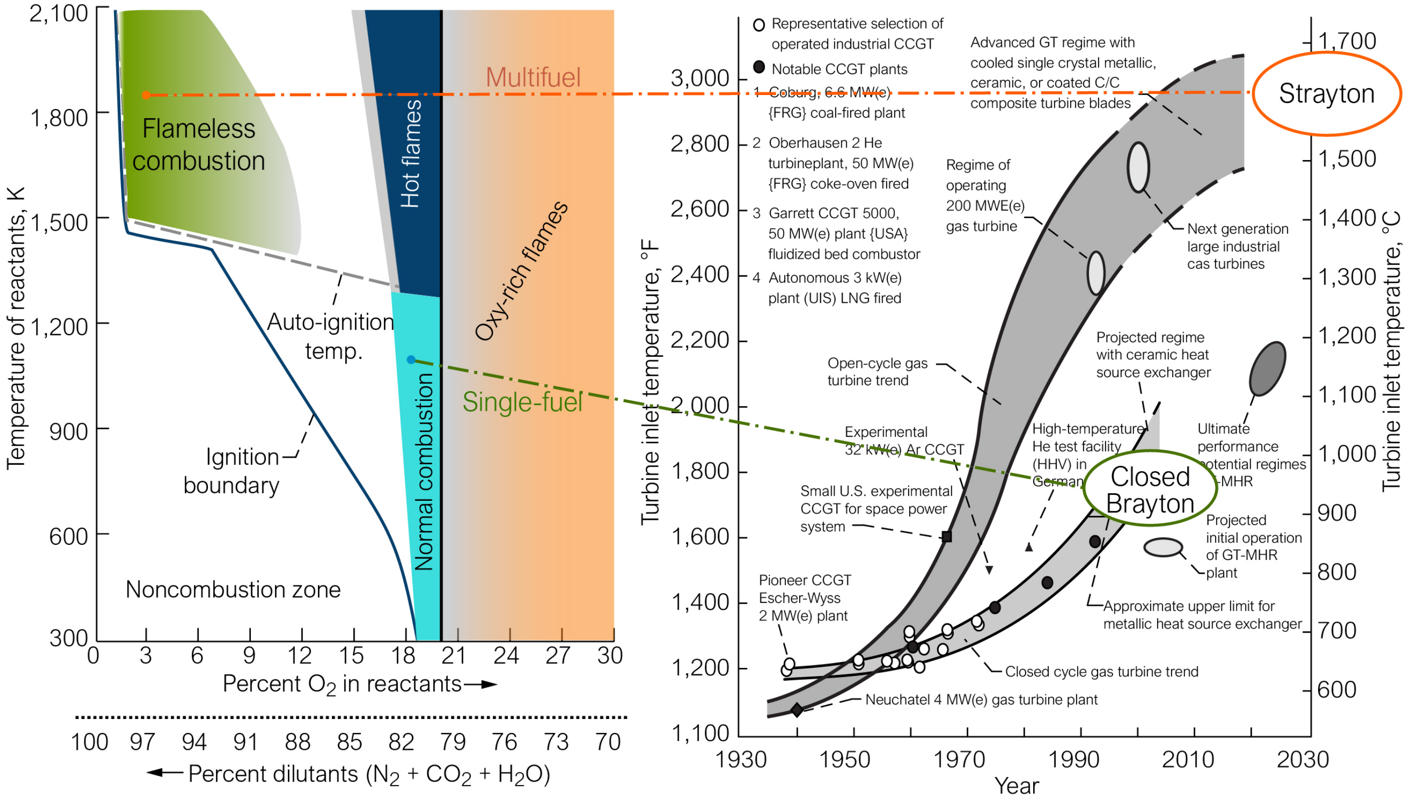


Figure 5.—Sealed Strayton cycle enables flameless combustion conditions (Ref. 3).

Fortunately, one of the key benefits of the Strayton cycle is that the turbine effectively becomes a heat acceptor for the embedded acoustic Stirling cycle (Figure 6). Therefore, the turbine is conductively cooled because the Stirling cycle accepts the heat. The combination of external combustion gas recirculation and internal conductive turbine cooling supports the 3% oxygen content and 1,500 K required for FLOX.

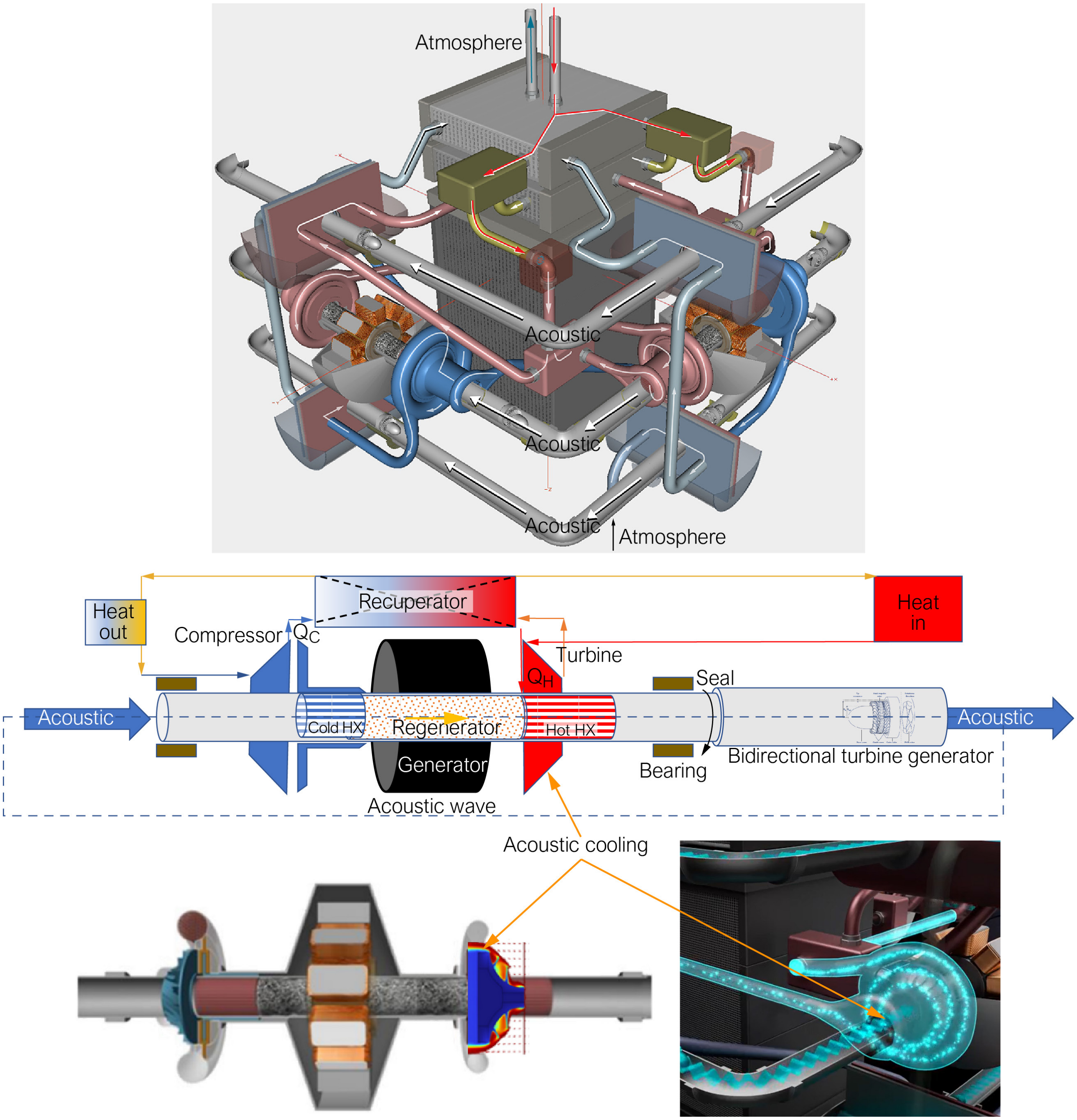


Figure 6.—Acoustic turbine cooling (Refs. 4 and 5).

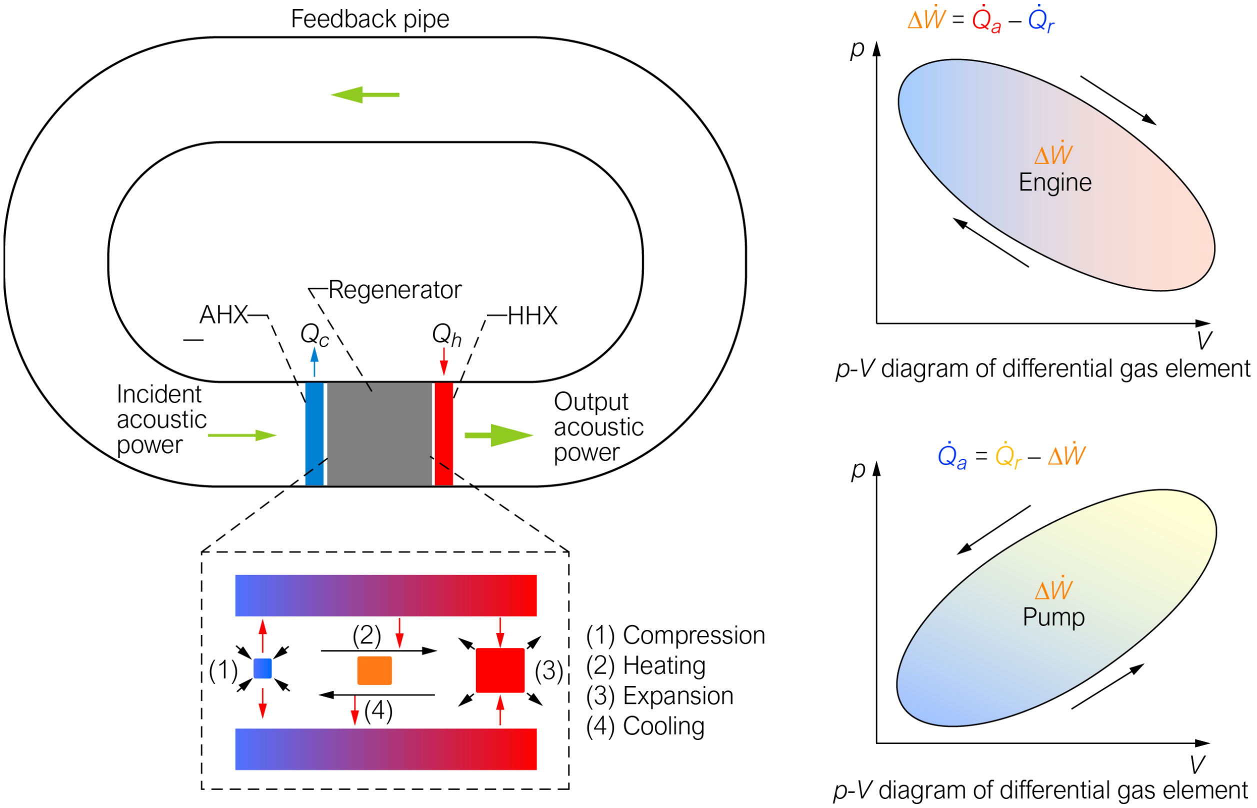


Figure 7.—Thermoacoustic effects in the regenerators of a thermoacoustic engine and cooler (Ref. 6).

The CSQG's acoustic turbine cooling (Figure 7) is the result of an acoustic wave traveling within the hollow shaft of the turbomachinery, collecting the heat from the turbine via the thermoacoustic effect (Figure 8), converting a portion of that heat into acoustic energy, and directing the remaining waste heat into the compressor exit. This CSQG video offers more information about this process:

https://nasagov.box.com/s/ak8i6bdxuphfhbxtrvnhubn8lvzqd0a7

The conductive cooling of the turbine required to maintain material temperatures lower than 1,200 K is often less than 40 kW, even at megawatt-scale power levels, due to the naturally compact high-speed turbomachinery in a closed cycle, which limits the overall convective heat transfer rate.

As a result, the embedded acoustic Stirling cycle is used predominantly for thermal management rather than power generation, but the overall system impact is significant, as Figure 8 illustrates. The figure plots specific work and efficiency curves across a range of temperature ratios from 3 to 7, which covers the full temperature range of today's Closed Brayton and turbofan engines. Note that the specific work or compactness of the CSQG is 6× greater than that of fuel cells (FC) and a factor of 2 more compact than diesel engines. In addition, it approaches a best-in-class efficiency of 70% without the need to use fragile open-cycle solid oxide fuel cells and turbine combinations, which is the approach commonly being explored today.

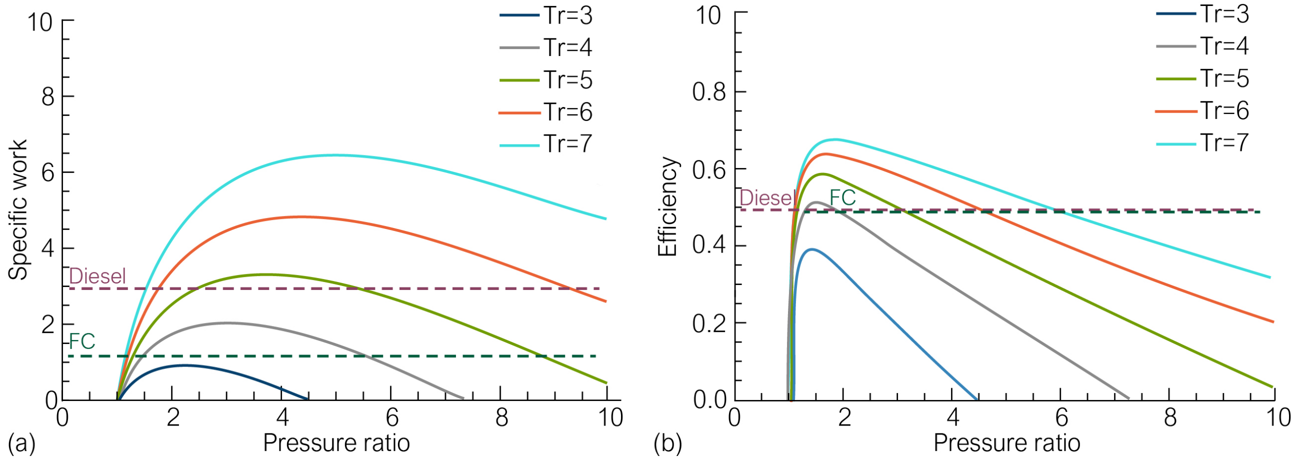


Figure 8.—Efficiency and compactness of CSQG versus temperature ratio (Tr) (Ref. 2).

Key Benefit: In short, the CSQG can achieve ZCI with PtL while also achieving best-in-class efficiency and compactness, without requiring prohibitive capital costs.

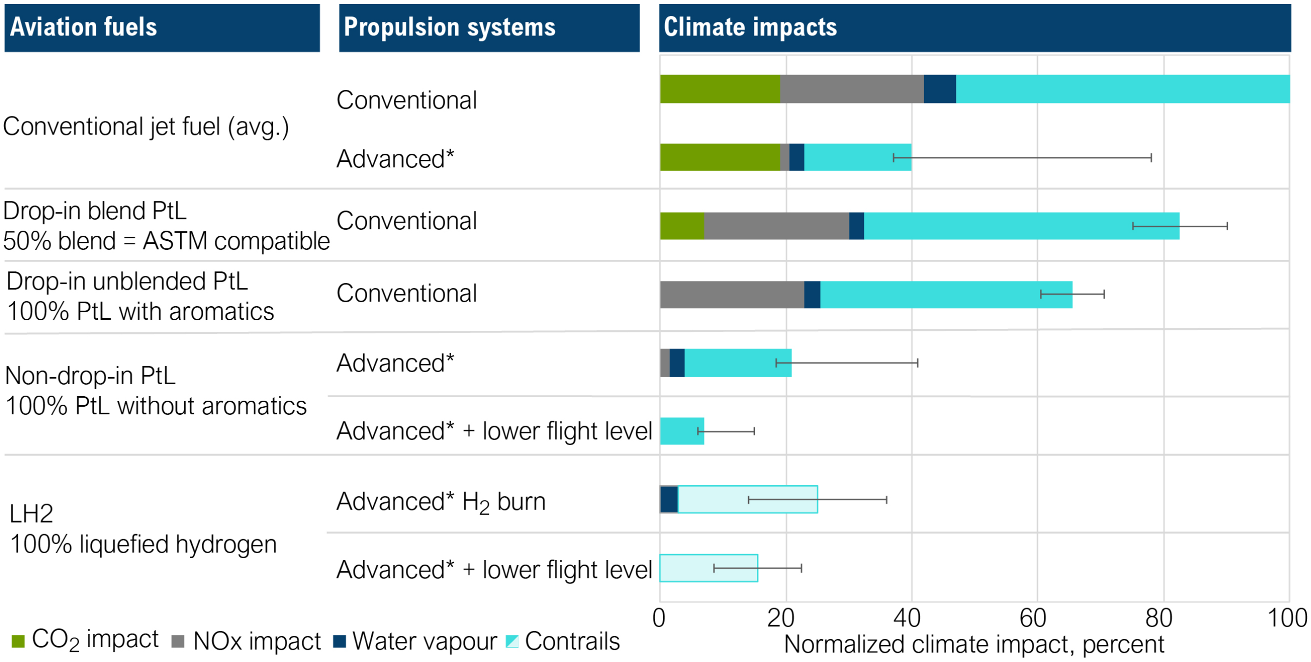
Climate and Infrastructure Impact

As mentioned previously, the combination of external combustion and acoustic turbine cooling allows the use of FLOX, recuperation, and catalytic reduction with any fuel. However, PtL and liquid hydrogen (LH2), a commonly used rocket fuel, are the only two net-zero fuels currently available that could be produced in quantities sufficient to satisfy a global demand. Unfortunately, the use of hydrogen has many associated safety challenges; the existing fuel distribution infrastructure is also incompatible with hydrogen. In contrast, recent studies (see Figure 9) indicate PtL has the potential to be a cleaner, safer fuel option than LH2. PtL is also compatible with the existing fuel distribution infrastructure, offering a game-changing reduction in capital costs.

Moreover, as Figure 10 illustrates, the current trend toward increasing production of LH2 worldwide naturally supports the production pathway for PtL. In addition, the European Union (EU) has very recently changed its policy to boost PtL production, as a recent report from Energy Intelligence suggests:

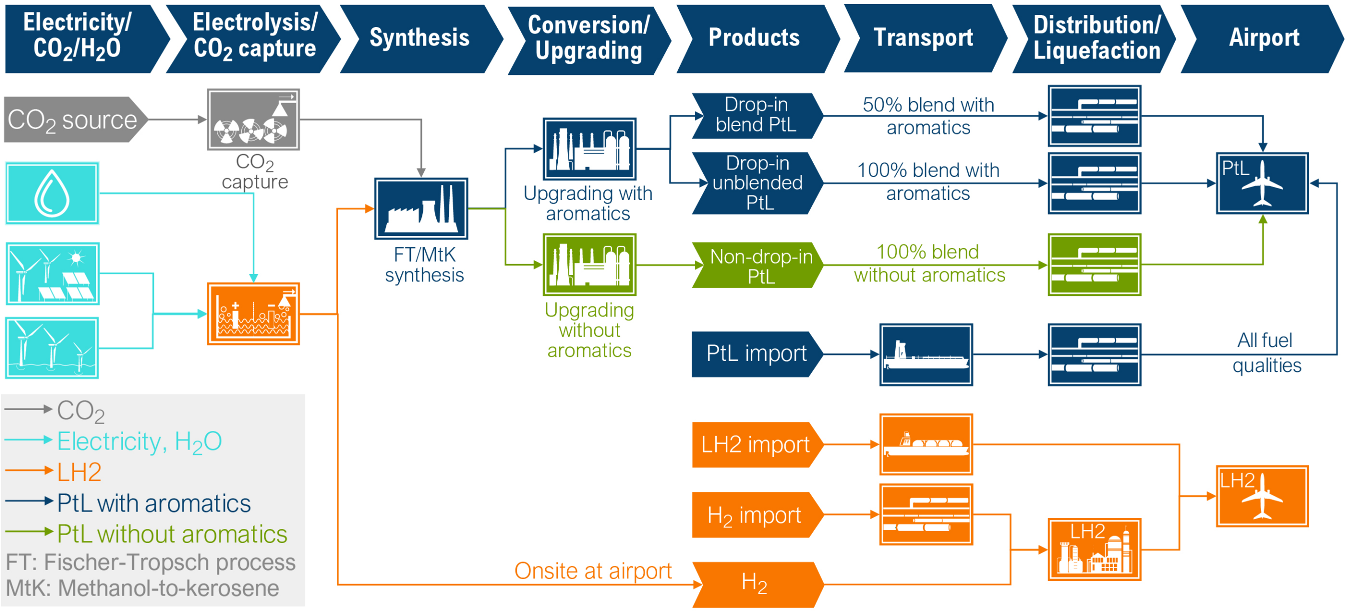
> “Last-minute tweaks to the EU's ReFuelEU policy have sparked a flurry of interest in so-called nuclear synthetic fuels. A deal was struck to allow power-to-liquids (PtL) sustainable aviation fuel (SAF) made from carbon-free nuclear power, alongside renewable energy. Other late additions to the EU SAF mandate legislation include a more ambitious 1.2% sub-mandate for PtL SAF starting in 2030, making progress on PtL SAF production more urgent. Advanced PTL SAF or e-SAF will need to make up at least 35% of the EU's entire jet fuel supply by 2050 under current plans.” (Ref. 7)

That recent policy shift suggests that most available LH2 fuel in 2050 will be used for PtL production in order to achieve 35% market share.



LBST based on normalized global emissions of B767 aircraft fleet (Silberhorn et al. 2022)
*Advanced = low-NOx/low-soot combustion technology

Figure 9.—Climate impact of scalable LH2 versus PtL (Ref. 8).



Drop-in blend PtL (50% blend compatible with existing ASTM); Drop-in unblended PtL (100% with aromatics); Non-drop-in PtL (100% without aromatics)

Figure 10.—Production pathways for LH2 and PtL (Ref. 8).

Finally, as the bar chart in Figure 11 shows, closed cycles are the only technology that truly has no climate impact when used with liquid hydrogen or PtL. Note that batteries are included as another ZCI technology, but their limited energy density and lifespan, as well as the associated disposal concerns, reduce their techno-economic feasibility.

Strategically, the United States is also currently expected to have greater PtL capacity than the EU, as the bar chart in Figure 12 indicates.

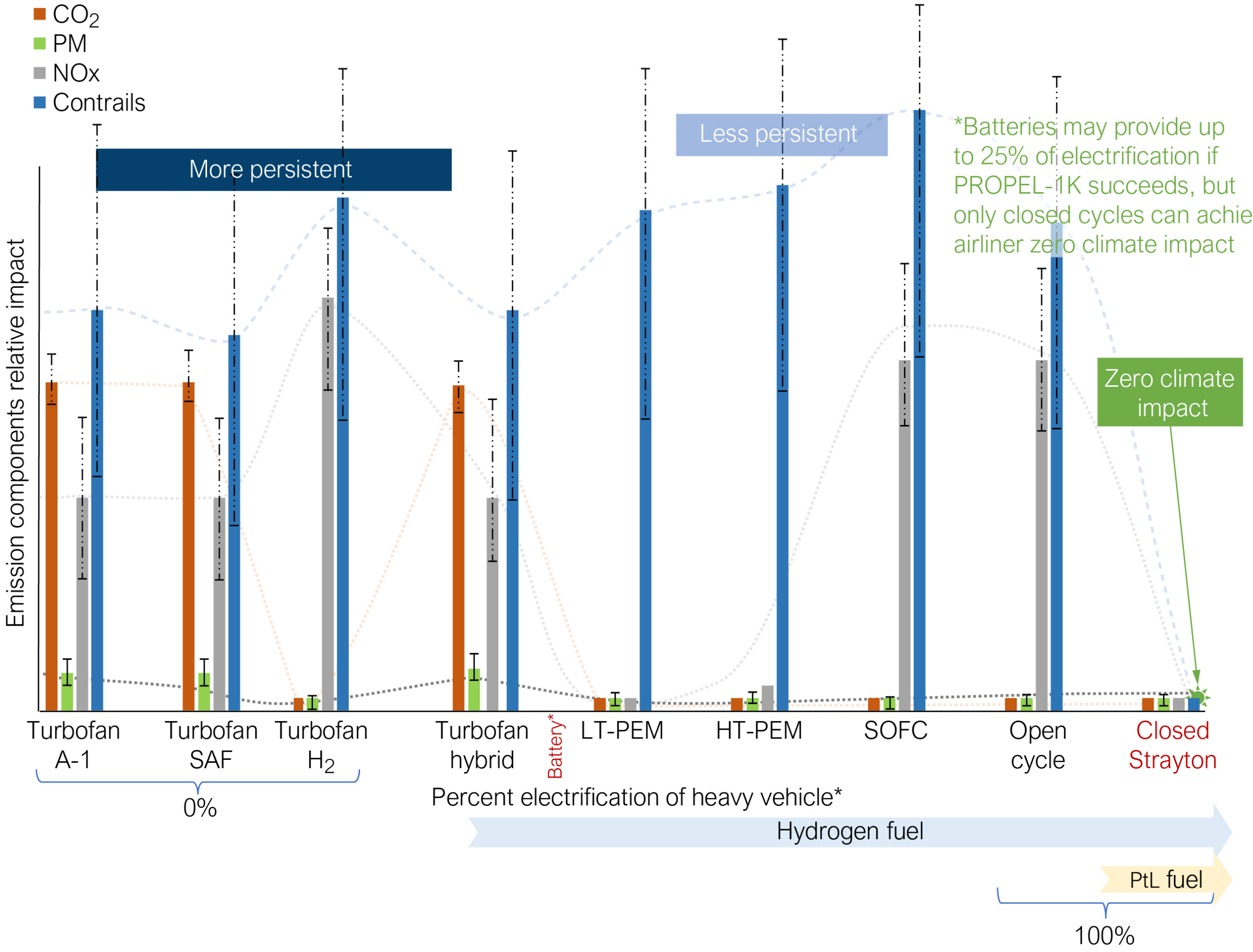


Figure 11.—Climate impact of various power source technologies (Ref. 9).

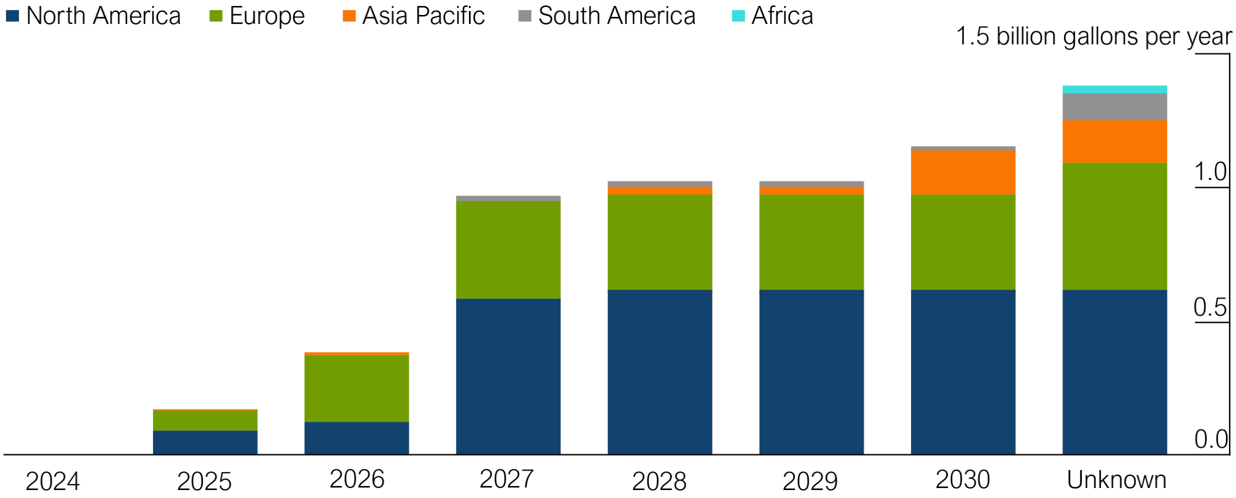


Figure 12.—Planned PtL global production capacity (Ref. 10). (Used with permission from BloombergNEF.)

The current worldwide push for LH2 production is driven by the early concern for CO_2 emissions, but recent studies suggest NOx and water vapor have potentially higher radiative forcing terms (Ref. 11). In the earlier context of only reducing CO_2 emissions, it made sense to pursue development of the low-temperature PEM fuel cells that require hydrogen. However, with the introduction of a FLOX closed-cycle technology with these efficiency and specific power metrics into the trade-space, PtL is likely to become the preferred unifying fuel. This will shift the technology development focus from batteries and hydrogen-fueled technologies into a more focused effort on PtL production and closed-cycle power generation implementation. It should also be noted that the ability to produce an infrastructure-compatible fuel locally using only water and CO_2 carries significant economic and practical advantages for both commercial and military logistics.

Key Benefit: Today, the CSQG is the only known technology that can achieve zero climate impact with PtL. Therefore, only CSQG will be compatible with the existing infrastructure. The use of batteries would require building charging stations; liquid hydrogen would require changing the world's fuel production, storage, distribution, and power generation infrastructure.

Design and Implementation Approach

As Figure 13 and Table 1 indicate, the primary components of CSQG technology have already been deployed commercially. The Closed Brayton generator was first demonstrated in the ML-1 prototype project with the U.S. Army in 1961; today, there are numerous Brayton generator manufacturers, including Barber Nichols, Brayton Energy, and Echogen to name a few. Brayton generators are currently employed in a wide range of vehicle propulsion systems, including trucks and UAVs, but their efficiency is limited to about 30%. Similarly, Stirling generator manufacturers like Sunpower, SoundEnergy, and Microgen have produced related products for homes and automobiles, but their low power density limits their techno-economic uses. However, when Stirling and Brayton generators are combined into a Strayton engine, the performance benefits are significant.

The CSQG combines two high technology readiness level (TRL) components, the closed Brayton and acoustic Stirling power convertors. The acoustic Stirling generators are arranged in a quad or square, with four repeated heat exchanger pair stages. Similarly, the closed cycle Brayton generator is arranged in a quad of four repeated compressor and turbine stages. The heat exchangers are located inside the quad structure to form a compact 10-MW generator with a profile of a 4-foot cube.

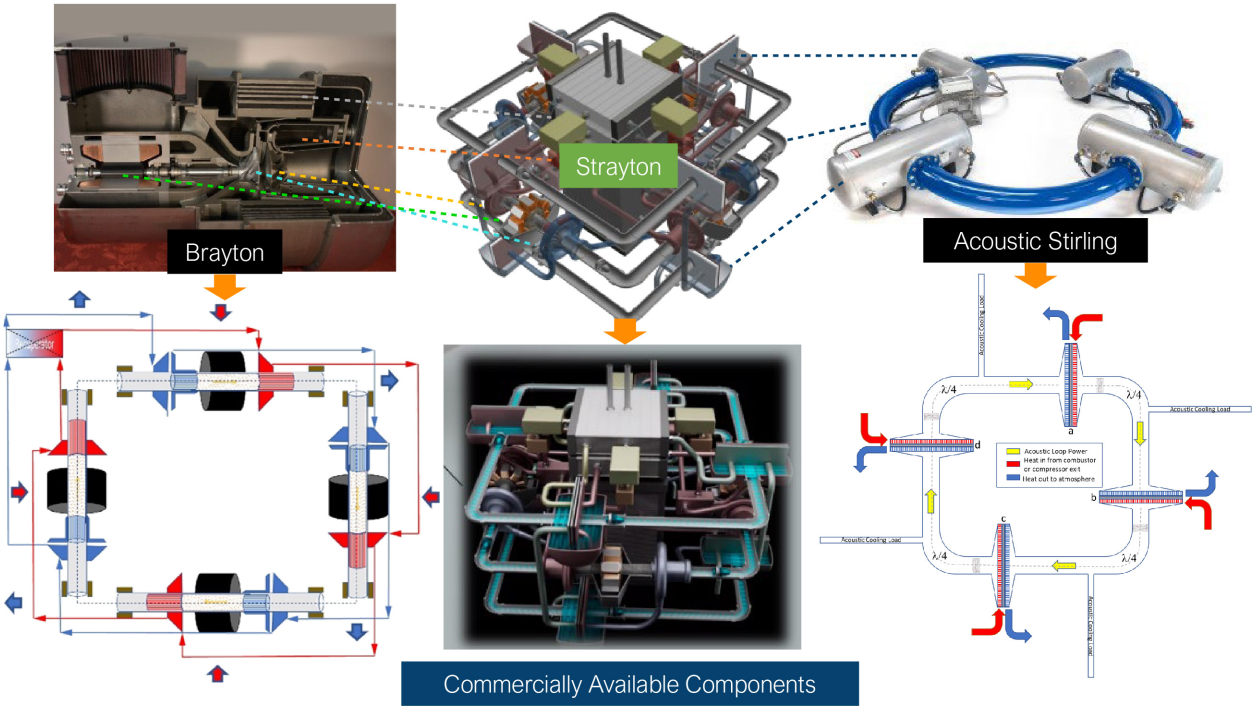


Figure 13.—Stirling integrated with Brayton = Strayton (Ref. 2).

Table 1.—Technology and Manufacturability Readiness, Advancement

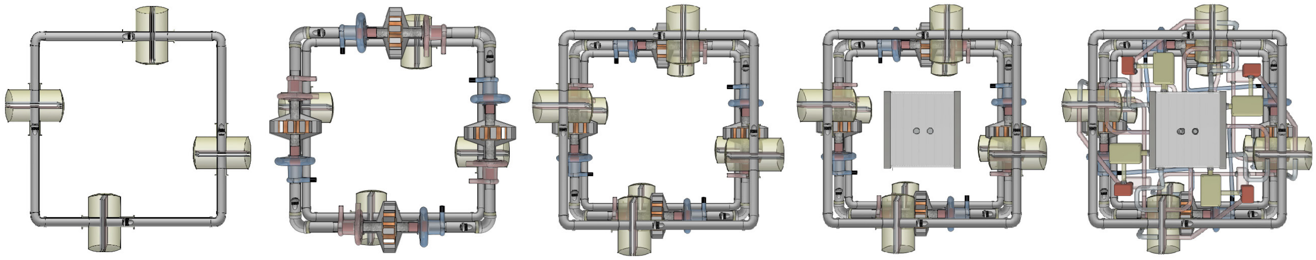
System	TRL	Deployments	Path to TRL 7
Closed Brayton	6	Many since 1960s	He-Ar working fluid
Acoustic Stirling	7	Soundenergy.com	Completed
Flameless combustor	6	ipg.energy	Combined with CSQG
CSQG	3	Preliminary design	Intergration of the parts

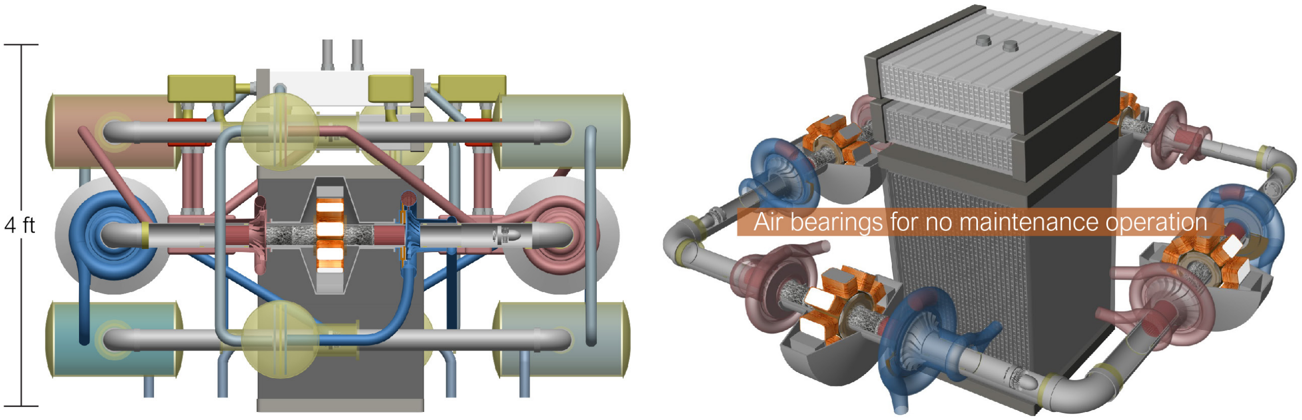
As illustrated in Figure 14, the CSQG consists of three acoustic loops, which are used to recycle waste hot-side heat, cool and recuperate turbine heat, and cool and recycle compressor interstage cooling waste heat, respectively. The middle acoustic loop includes the radial compressor, turbine, and generator. The interior block is the recuperator. Both the Brayton and Acoustic Stirling cycles are arranged into a four-stage loop. Integrating four Brayton and four acoustic Stirling stages into a single engine has a number of advantages, including minimizing the required heat exchanger mass, optimizing the compressor and turbine performance, and eliminating the need for an acoustic resonator.

Key Benefit: The CSQG's geometric synergy permits integrating multistage Brayton and Stirling cycles and the heat exchangers into a compact, power-dense, cube volume.

Cooling Capability

In addition to providing clean, quiet, and efficient electric power, the CSQG can also directly provide thermal management of a vehicle’s low-grade electrical waste heat by using the acoustic waves produced in the three acoustic Stirling quad loops. As illustrated in Figure 15, heat from the Strayton cycle turbines, compressor interstage cooling, and combustion heat exchanger losses can be used to generate an acoustic wave, which can then be used to provide refrigeration using the thermoacoustic effect, with no moving parts on the vehicle.


Acoustic interstage cooling quad — Closed Strayton quad — Acoustic interstage heating quad — Central recuperator — Connected system



Mostly hollow tubes with dishwasher-sized heat exchangers in the center.

Figure 14.—CSQG assembly (Ref. 2).

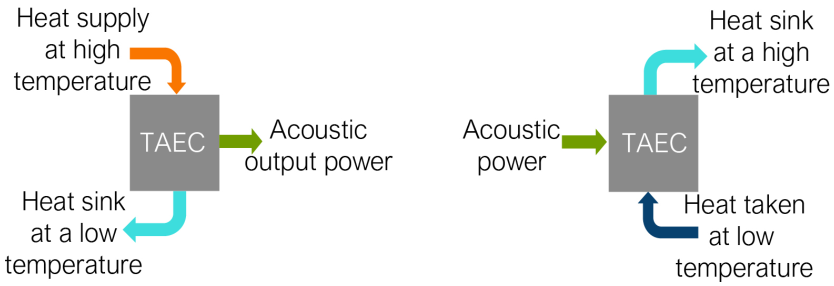


Figure 15.—Acoustic heat pumping (Ref. 2).

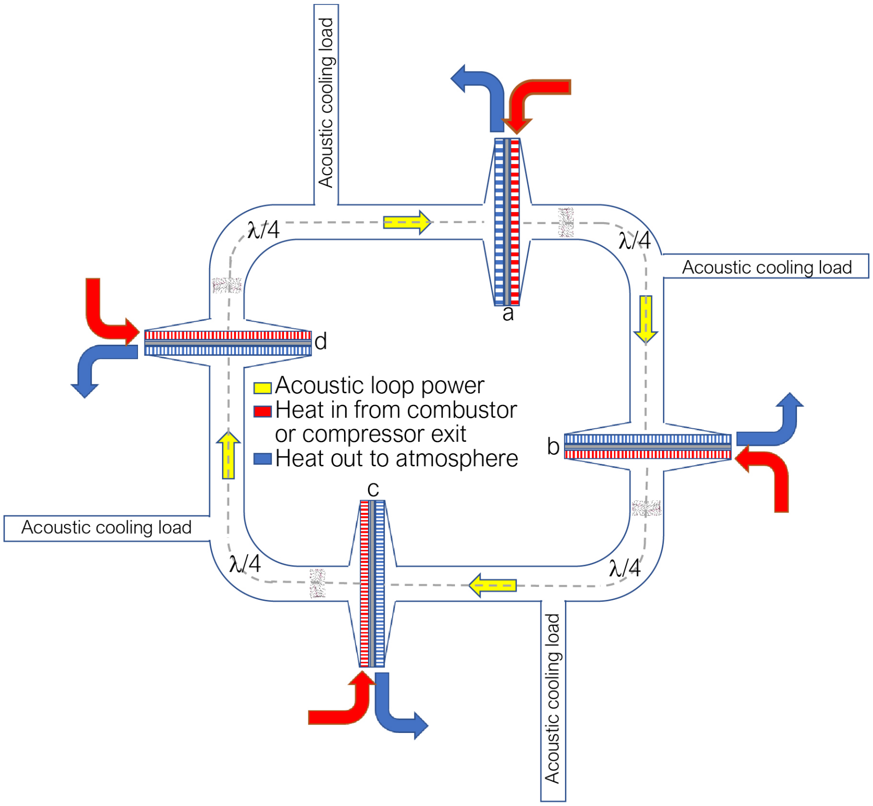


Figure 16.—Acoustic wave generation for cooling (Ref. 2).

As indicated in Figure 16, the heat collected from the four stages in the three acoustic Stirling loops is converted into an acoustic wave via the thermoacoustic effect. Some of the acoustic energy generated in the main quad loop is subsequently used to support the acoustic heat pump refrigeration of sensitive electrical components.

In this fashion, the CSQG synergistically provides both electric power and active cooling for the entire vehicle system with no moving parts. For example, as shown in Figure 17, future superconducting machines will require both power and cryogenic cooling; CSQG can provide both electric power from the Brayton rotating turbomachinery generator and cryocooler heat pumping with the acoustic energy produced in the three acoustic quad loops. Recent tests have confirmed it’s possible to send an acoustic wave more than 30 feet to provide acoustic heat pumping anywhere on the vehicle. The same acoustic cooling system can provide for both cryogenic and ambient cooling to replace the current generation of pumped vapor compression systems and heavy cryocoolers.

Key Benefit: CSQG’s acoustic wave generation solves both the power and vehicle thermal management problem in a single compact, scalable unit. As the power demands increase, so does the thermal management capacity because the acoustic energy generated scales with the level of electric power generation.

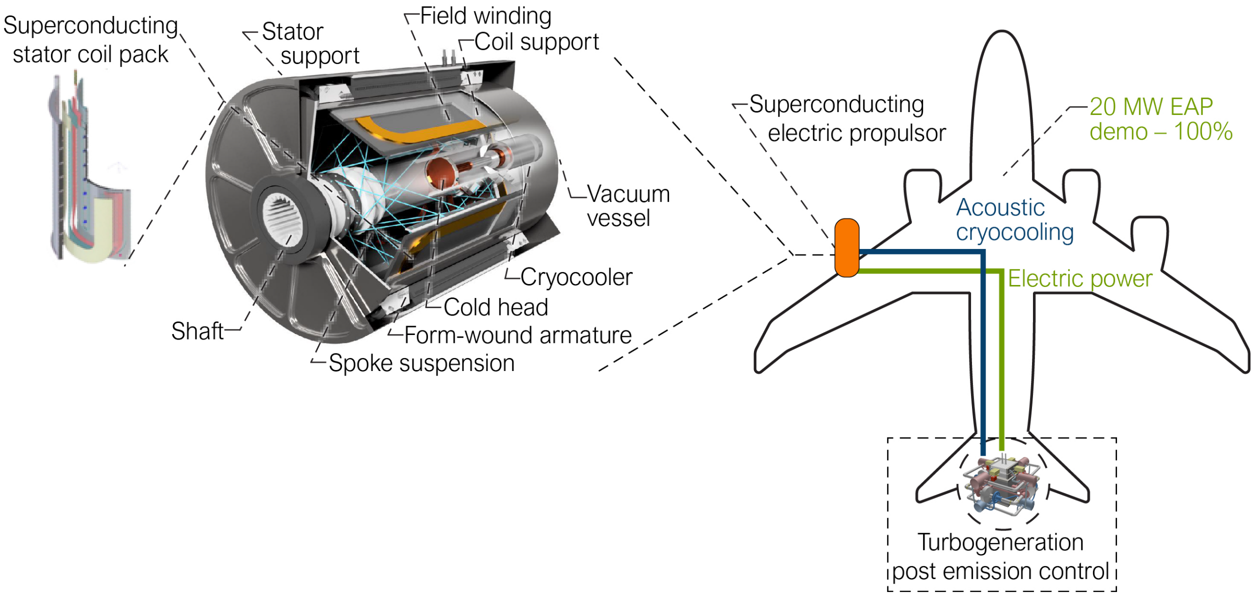


Figure 17.—Synergistic power and cooling for the vehicle (Ref. 2).

Summary

This technology supports the growth of a new techno-economic clean energy global ecosystem based on scalable synthetic fuels that are compatible with today's infrastructure. At the same time, it allows for zero climate impact in the future without requiring performance-limiting batteries or infrastructure-limited hydrogen-fueled technologies. The CSQG combines all the benefits of fuel cell efficiency, diesel compactness, gas turbine load response, and Stirling turndown ratio into a quiet, clean, low-maintenance, low-cost, multi-environment, multifuel-compatible generator (Table 2).

Table 2.—Comparison of Alternative Power and Propulsion Technologies (Ref. 12)

Criterion	MCFC	PEM	Diesel	Gas turbine	Stirling	CSQG
Efficiency over a wide range of loads	Flat	Flat	Best at >75% load, poor at partial load	Best at >80% load, very poor at partial load	Best at 40%, reasonable at part load	Flat
Response to load changes	Slow at startup	Fuel/reformer dominated	Good	Fast	Fast	Very Fast
Life	1,000 hours	10,000 hours	20+ years	20+ years	30+ years	30+ years
Noise, vibration	Low	Low	High	Medium	Low	Low
Power range	500 to 2,500 kW, modular	20 to 2,500 kW, modular	Up to 68 MW	Up to 50 MW	Up to 25 kW, modular	Up to 10 MW, modular
NOx, CO, HC emissions, CO_2	Very low, reduced CO_2	Very low, reduced CO_2	Medium	Medium, no CO_2 benefit	Very low or zero	Very low or zero

Key Attributes: CSQG combines the advantages of zero climate impact with superior vehicle performance:

- **Scalable and modular** with benefits applicable to any vehicle and power level
  - Stackable and compact closed-cycle generators
  - Requires no abrupt S-curve change in technology and budgets
- **Compatible** with existing infrastructure and vehicles to avoid disrupting services and economics
  - Maintains stakeholder support through different political climates.
  - Industry can focus on a single fuel type (fossil and future synthetic version)
  - Recognizes industry inertia and life of current fleet
- **Competitive** by maintaining today's *performance* and *cost* expectations with a clear path to ZCI.
  - Path to achieve net-zero CO_2 with existing fleet with superior performance
  - Path to achieve ZCI with next-generation fleet with superior performance

CSQG makes possible an optimal global energy ecosystem that is compatible with the existing infrastructure, improves vehicle performance, provides both power and cooling naturally, and protects the environment (Table 3).

Table 3.—CSQG Attributes

Requirement	Compliance
• High energy efficiency	• 70%, best in class without sacrificing reliability
• Supports the use of fossil fuels, alternative fuels or nuclear power	• Flameless oxidation supports any fuel with little or no GHG emissions
• Scalable system architecture	• 40 kW to 10 MW
• Ease of recharging/refueling	• Supports today's and tomorrow's fuels and small modular reactors (SMRs)
• No loss of performance	• Exceeds capability and reliability of current diesel engines and future fuel cells
• Compatible with harsh environments	• Sealed system works anywhere with no engine maintenance required
• Meets all operational requirements without losing capabilities due to switch from fossil to alternative fuels	• Higher efficiency in a sealed system improves operational performance with either fossil fuels or alternative fuels of the future
• Silent/low-noise operation	• Quiet, sealed system
• Lifecycle costs are competitive with conventional solutions	• Requires no platinum or rare earth metals. Anticipated capital expenditure is $142/kW. Reduced operating expenses.

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