White Paper

THE FUTURE OF INTERNAL COMBUSTION ENGINES AS SEEN BY ROLLS-ROYCE POWER SYSTEMS

This white paper is intended to summarize the position of Rolls-Royce business unit Power Systems on the future of internal combustion engines (ICE) in the application areas and industries of relevance to us, including marine, industrial, and power generation applications. It aims at shareholders and stakeholders with general interest in these industries.

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A Rolls-Royce solution

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A Case for Change

Internal combustion engines made their way into many applications with the invention of spark ignition gasoline engines and compression ignition diesel engines before the turn of the 19th century. Both principles are the prevailing ones in use still today.

In general, ICE range from small (single digit kW or even smaller) to very large (up to ca. 80.000 kW) power output. Most relevant for Rolls-Royce Power Systems are off-highway engines in a power range starting at 560 kW up to around 10.000 kW, because they are at the core of the power trains in Power System's end markets. This market segment represents a specific part of the overall global ICE market, which is dominated by on-highway applications (Table 1).

Type of ICE sold in 2020	No. of units p.a.
On-highway (Diesel, Gasoline & Gas)	80 Mio. units
• thereof Diesel > 20kW	20 Mio. units
Off-highway > 20kW	2 Mio. units
• thereof Diesel > 560 kW	67 k units

Table 1
On-highway vs. off-highway unit numbers [i]

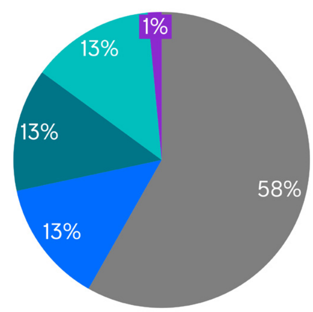
In the most recent decades of ICE development, the main focus was on the increase of power density, on the performance map (aiming at optimizing fuel consumption at given load and speed profiles), on efficiency improvements and on emissions reduction. In recent years, the increasing focus on de-carbonization of the power train of on-highway applications has also reached many applications in the off-highway markets.

While many propulsion related discussions of today's ICE are revolving around the high volumes of engines produced for the automotive industry, this paper addresses the future of the ICE through the lenses of our applications and industries. Nevertheless, it goes without saying that certain technology advances in the on-highway market were and will be transferred and innovated into the off-highway market and thus also into Power Systems products and applications.

The key applications of concern to Rolls-Royce Power Systems and this paper are:

- Power Generation:
  ICE-driven generator sets for mission critical & backup power in hospitals, data centers, etc.
- Power Generation:
  Generation of continuous electrical power by diesel- or gas engine driven generators. For example, combined-cycle heat and power plants or grid stabilization in remote areas with no other viable form of electrical power generation
- Mining, Oil & Gas and Rail:
  Usage of ICE as drive train solution for transportation and machinery equipment
- Marine and Yachting:
  ICE system solutions for the propulsion of vessels
- Governmental:
  High performance ICEs for propulsion and onboard power generation on land and sea.

Table 2 shows the market for diesel-based ICE units according to the application split. It is divided into a high number of units deployed in mission critical and power backup applications and less than 30% in transportation.



Application	No. of units p.a.
Off-highway Diesel > 560kW in 2019 (no COVID impact; incl. DMU 130-560 kW)	67.000
Power Generation: Mission critical & backup	39.000
Power Generation: Continuous power & peak shaving	9.000
Mining, Oil & Gas, and Rail (incl 130-560 kW DMU)	9.000
Marine / Yacht	9.000
Governmental	1.000

Table 2
Market split of off-highway ICE units p.a. [ii]

Today's off-highway market is dominated by fossil-fired ICEs which cause a significant amount of CO_2 emissions. Based on own calculations, we estimate the overall CO_2 emissions of the off-highway market with Diesel engines >560kW to be approximately 690 Mt CO_2eq in 2019 (following the SBT calculation method[vi]).

Given that we have a limited, accumulated budget for Green House Gas (GHG) emissions to keep global warming well below 2°C[1] or preferably 1.5°C[2] compared to pre-industrial levels, ICE-based applications play a key role in reaching climate goals.[iii]
Off-road transport (6%) and power and heat generation (42%) account for almost 50% of the global CO_2 emissions from fossil fuel combustion in 2020.[iv]
Hence, the use of pure fossil-fired engines must be reduced drastically and with that the deployment of ICE, or even the substitution thereof, must become CO_2 neutral or CO_2 free, eventually.

Fuel efficiency improvements and exhaust emission reductions of ICE, mandated by ever stricter emission regulations (introduced e.g. by IMO, EPA), have made significant steps over the past few years and will continue to do so. However, it would not be near way enough to reach the GHG 2030 reduction ambitions and by that the 2050 net zero ambitions to stay below the 2°C warming increase scenario. It is for this reason that new technologies must be developed and deployed, which will gradually replace conventional fossil-fired ICE.

What are the potential ways forward?

Besides continuous fuel efficiency and emissions reduction efforts for fossil-fired ICE, the following technological principles have the most leverage for emission reduction and promise substantial GHG emissions improvements:

a. Continue with fossil-fired engines but capture the GHG emissions at the "exhaust pipe", i.e. capture and store the emissions so that they would never be emitted to the earth's atmosphere. Since this approach is not yet relevant in our fields of application, it is not further discussed in this paper.

b. Usage of combustion engines with sustainable, i.e. non-fossil, fuels (synthetic fuels or e-fuels often subsumed under "Power to X" (PtX) fuels such as eDiesel, eHydrogen, etc., but also 2nd generation Biofuels). Hence, the aim is to reach a CO_2 net zero operation of combustion engines. Depending on fuel type, it either relates to a fuel that revokes as much CO_2 from the air, binds it from biogenic sources or from other CO_2 emitters for its production as is emitted by the use in the ICE when burning that fuel. Or it relates to fuels, e.g. hydrogen, that would not at all emit CO_2 at the exhaust pipe.

c. Switch to alternatives for combustion engines. Depending on the application this can be an electric motor, if rotatory mechanical power is needed, or a static solution, like a fuel cell or battery. Products and infrastructures leveraging solar and wind energy to charge a battery or produce green hydrogen are already available, although their amount and accessibility are very dependent on country and location.

Taking into consideration technical, commercial, and regulatory constraints, besides the important ecological aspects, combinations of the above with today's fossil-fired fueled ICE are possible, e.g. electro/diesel hybrid solutions for the transport sector.

Regardless of whatever principle or combination of technologies is chosen, we believe it is of utmost importance to consider the complete GHG balance and thus the complete value chain "from well to wheel" or in terms of the product lifecycle "from cradle to grave."

Expected availability and feasibility of technologies

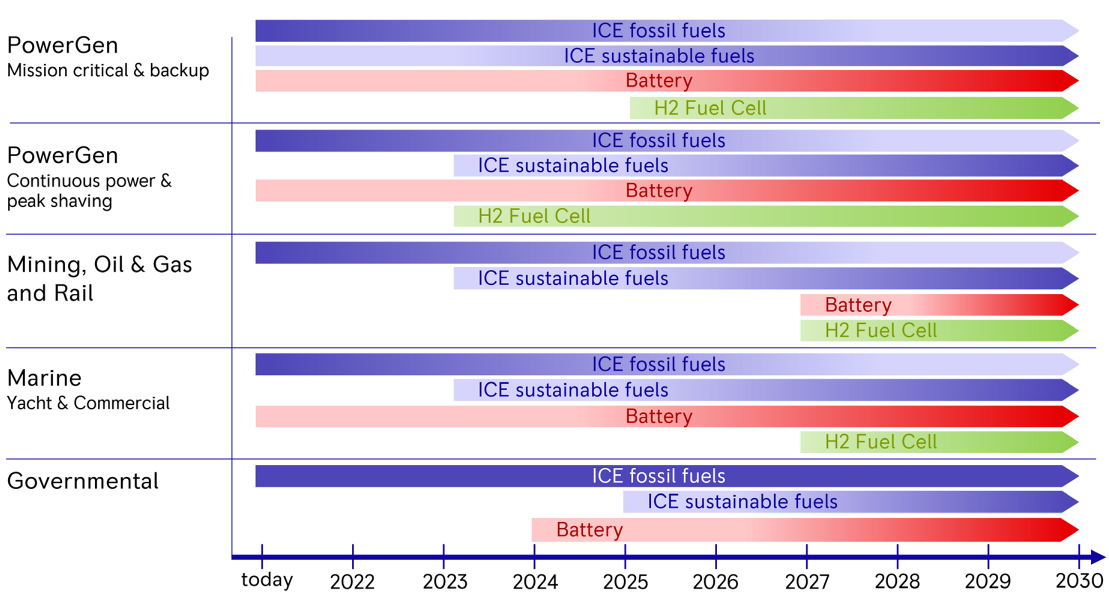


Figure 1
ICE application share and substitute technologies (internal source)

1 IPCC ref.: 1170 Gt CO_2eq
2 IPCC ref.: 420 Gt CO_2eq

For example, with respect to the GHG emissions and targets, it is of no use to burn a fuel in an ICE that does not emit CO_2 (say hydrogen), if the fuel was produced with the help of CO_2 emitting energy sources (e.g., electricity from fossil-fired power plants). Since many chemical processes, like creating hydrogen, require electricity, it is crucial that the latter is produced, transmitted, and stored in an ecological friendly way, i.e. by renewable means. Hence, sector-coupling and alignment of the power generation industry and energy-consumption industries will become very important

Figure 1 gives an outlook of the expected relevant technologies needed for the market transformation as we see it today. Independent of the underlying GHG scenario the figure shows our expectation of the still important role of ICE in the coming years. However, it is clearly competing with the rise of battery and fuel cell technology.

Implications on market demand scenarios for ICE and ICE-substitutes

Given the above technical options and estimated time spans as indicated in Figure 1, we believe that the power demand for our applications and thus the ICE and alternative-to-ICE demand will co-exist for many years. However, the distribution of the variants will evolve with an underlying pattern which is discussed in this chapter. We derived our market expectations assuming three scenarios of emission reductions based on IEA and IPCC reports. One scenario with today's policies and decisions in place (scenario 1), one which would assume much stricter policies and a very strong push for and availability of a green hydrogen ecosystem (scenario 2), and one with similarly strict policies like scenario 2 but the hydrogen ecosystem is not build as fast and sustainable fuels are ramped up accordingly.

The translation of the global warming scenarios onto our markets allows the creation of strategic roadmaps for the development of technologies. In June 2021, the Rolls-Royce Group committed to a GHG reduction goal within the context of the "Business Ambition for 1.5°C" campaign.[V]
As can be seen in Figure 2, independent of the scenario, the share of the ICE as single solution or part of a hybrid system will still be between 60-90% by 2030. With orientation towards the third scenario and possibly even a stronger hydrogen pick up, ICE will still make up two thirds or more of the deployed portfolio. However, to meet the underlying emission values, one half of the ICEs would need to be fueled by sustainable fuels.

To what extent such a scenario will become reality depends on a number of drivers to be in place. The major ones are sustainable finance standards, market framework regulations like the CO_2 price or CO_2 emissions limits, a global alignment on standards, and the energysupply chain including the availability of infrastructure.

As result of these scenarios we are preparing for a technology mix of ICEs and electrical (incl. hybrid and fuel cell solutions). But whatever the detailed mix, we strongly believe that battery systems will play an increasingly important role in all our applications. Especially in combined technology solutions, batteries will allow to cope with the inherent peak demands in our applications.

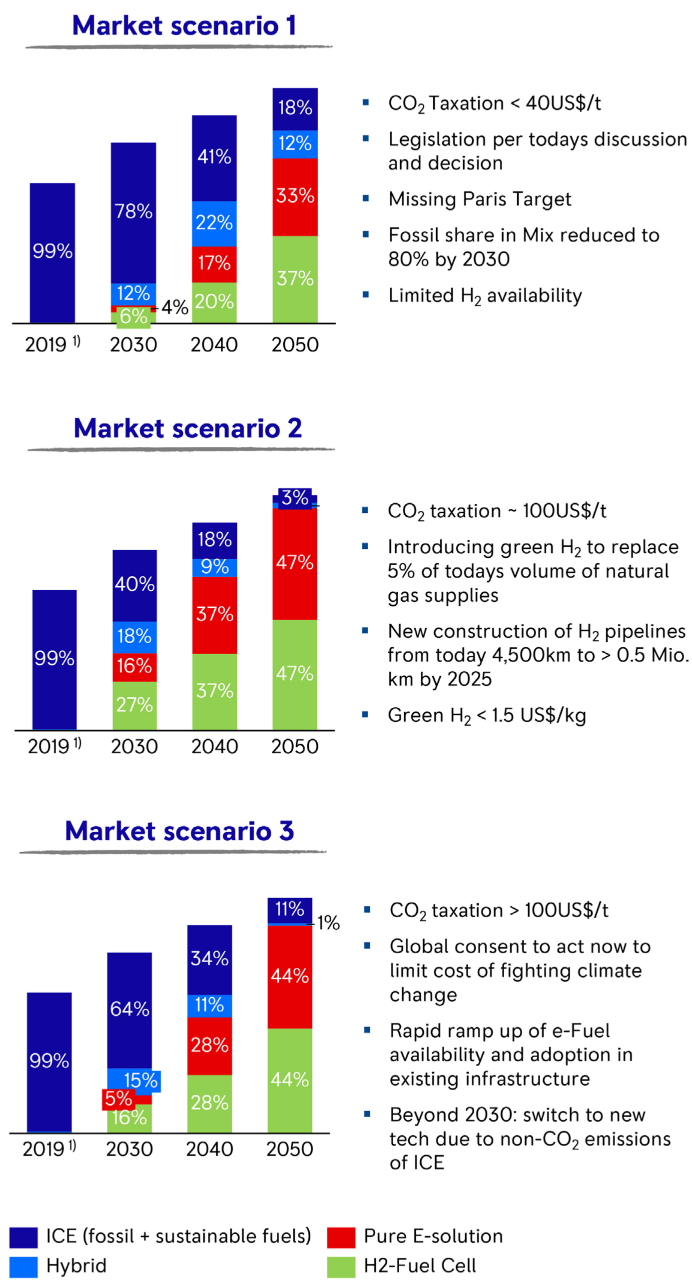


Figure 2
Market transformation scenarios (internal source)
1) normalized on base demand 2019

In general, but specifically also in our fields of application, purchase volumes of battery systems will increase exponentially. They represent a significant part of total costs in hybrid and electric systems (approx. 25-30% of a marine/rail hybrid system).

It can be expected that the relevant success factors for adoption of battery systems, namely price and energy density (gravimetric and volumetric), will continue to improve over the next decade, especially also in our fields of application as they have already in other application domains. For instance, in the automotive industry the battery prices dropped almost 90% over the last ten years. Technology drivers for further improvements in battery technology are found outside of our industries. Examples include the automotive sector, where energy density, fast charging performance, durability, etc. are crucial, or in the utility sector where high energy and long storage times are a must. Thus, it will not be feasible to develop own battery technologies tailor-made for our fields of application. However, the application-specific packaging of battery-based systems will be a decisive factor due to the low volume/high mix nature in our industries. It will be key to harmonize and standardize on an architecture with re-usable modules across our industrial applications – at the same time we need to be able to benefit from battery technology advances which we will see every few years going forward.

Putting the pieces together towards what is viable

GHG ambition and new technology deployment must be viable for the diverse customer segments and applications at the time of installation and over the life cycle of the solution. The following four key aspects are to be considered when deciding on options as outlined in the previous chapters.

1. Installed base

In an industry where asset lifetime spans over decades, the management of the installed base and the customer relationship are key. Given that off-highway vehicles or buildings and infrastructure are built around the drive systems, i.e. around the ICE, fulfilling future GHG requirements must consider the specifics of the installed base and related application realities.

Rolls-Royce Power Systems internal calculations show that following the Science-Based Targets (SBT[vi]) definition the lifetime GHG emissions of our products deployed in a given calendar year are approximately 1,000 times higher than the annual GHG emissions of all sites of Rolls-Royce Power Systems combined[vii]. Thus, the use of CO_2 neutral fuels for any products deployed into the field or reduction of total emissions through technology combinations (e.g. gas ICE + battery) would have a high leverage on reducing GHG emissions still in this decade. It will not only promote different technologies like PtX fuels or batteries, but also ICE conversion kits for alternative fuel use
(e.g. natural gas ICE to hydrogen ICE). The latter will help to secure investments in the already installed base or the soon-to-be installed base.

2. Total Cost of Ownership

Total cost of ownership (TCO) is key to customers, especially with continuously running equipment. Most of our ICE are operating in a range above 3,000 running hours annually. The reduction of operational expenditures is a constant driver for further improvements of ICE.

TCO also incorporates cost of fuel and related taxes, fees for emissions and a regulatory framework that safeguards investments with long pay back periods. The cost of sustainable fuels is determined by the cost of feedstock, of power and of the chemical transformation process. First studies show possibilities for competitive costs comparable to biofuels, but this is strongly dependent on the availability of accessible and stable renewable energy sources.[viii ix]
Our analysis and estimations predict higher average costs for sustainable fuels, in a range of 2-3 times compared to fossil fuels by 2030. This would increase customer TCO unless there were balancing measures in place related to the use of fossil fuels.
However, real future TCO will also depend on cost of emissions, especially for emitted CO_2. Taking it into consideration, future CO_2 pricing can potentially offset additional cost for sustainable fuels, because the reduction or complete avoidance of CO_2 emission costs will have a positive effect on the TCO.
Lastly, the regulatory framework has to be such that there can be a high confidence that today´s investments will yield the calculated return. Hence, customers and investors must be re-assured that the solutions conceived today and deployed in the near future are compliant with the standards and policies in the long run. For instance, the IMO must give guidance with respect to emission requirements of the future. A patchwork quilt of standards must be avoided under all circumstances.

If the above TCO criteria are favourable, CO_2 neutral and CO_2 free fuels for combustion engines are a viable alternative for many years. It would avoid the high costs and risks of entirely re-designing the primary applications (like ships, rail cars, etc.) and allow to continue with proven designs while still meeting the GHG reduction ambitions.

3. Feasibility of bridging technologies

Bridging technologies are needed to mitigate possible high costs and risks for applications in switching over to more disruptive technologies.

We expect sustainable CO_2 neutral fuels to play an important role, especially until CO_2 free technologies (e.g. fuel cells) reach a higher level of maturity. Our customers are already strongly demanding these fuels for use in their existing fleets. Especially "drop-in" fuels like sustainable diesel or sustainable methane have the benefit of using existing infrastructure for distribution. Hydrogen fuelled ICE and hybrid propulsion are further options to reduce emission impacts to the environment across all segments and build the bridge towards net zero propulsion.

Rolls-Royce Power Systems clearly sees ICE as a viable bridging technology towards a CO_2 neutral economy. Since the development of new CO_2 free substitute technologies for ICE need time, we expect more than 60% of our delivered products still being based on ICE technology in 2030. To reach the third scenario in Figure 2, our newly sold portfolio in 2030 would require a 35% lower absolute emission of GHG compared to the portfolio in 2019.

Enabling ICEs to be a bridging technology means to adapt today's and future ICE platforms to a wide use of CO_2 neutral fuels. Currently available Gas-to-Liquid (GtL) and Hydrotreated-Vegetable-Oil (HVO) fuels have similar characteristics compared to future CO_2 neutral PtX fuels. They can be used to develop and demonstrate the PtX fuel usage capability of ICE platforms, until PtX fuels are available in large quantities. Taking hydrogen into consideration, natural gas ICEs with options to retrofit to partial or full hydrogen combustion, are not only a bridging technology but a CO_2 neutral, or even CO_2 free technology for the future.

4. Market- and application specific priorities

While we see a momentum in the market and customer base to reduce GHG emissions, the willingness to deploy new sustainable technologies is very different across customer groups. Regulatory framework and policies are a major driver, but also the individual interest of customer groups. A good example is the Governmental, Naval and Defence customer group: while priorities still are availability, safety and reliability of their products, many of these customers also aim to achieve net zero emission in 2050.* Here, alternative solutions will become more interesting only when they have proven that they indeed offer similar technological characteristics compared to mature drive and propulsion technologies.
On the other hand, the customer segment of stationary power generation is more progressive with new technologies, especially if emission reduction can be monetized in their business cases (certificates or reduced CO_2 tax) or if permissions to build sites are contingent upon low emissions.

Concluding from this, technological change will not happen simultaneously across all customer segments. The different applications will evolve at their own pace and will likely go with different technological concepts. Unfortunately, there will not be a one-fits-all underlying technological basis, like a diesel or natural gas ICE has been, but rather a number of coexisting technologies for many years to come. The ICE will not vanish as a key technical option in the future. Even in 2050, ICE will likely be the base technology for some specific applications.

Considering the key buying criteria related to fossil fuel (as presented in Figure 3) and assuming an acceptable TCO assessment, availability of bridging technologies, and the specific priorities of the applications, we expect a change in technology split as shown on the right side of Figure 3.

While we believe that ICE technology will be partially replaced by new technologies in 2030 subsumed under the category "Electrified & hybrid", the level of substitution is strongly dependent on the application. ICE will still have a big share in 2030 in all customer segments. Naturally, the fuel source plays an important role. Liquid and gaseous CO_2 neutral fuels will play their part already. To that end, customer studies are under way where retrofit options are considered in the new design of engine rooms, etc. so that vehicles or vessels do not need to be re-designed or scrapped when propulsion technology requires changes. Retrofit options can include anything from fuel type changes over hybrid solutions to entirely new technologies.

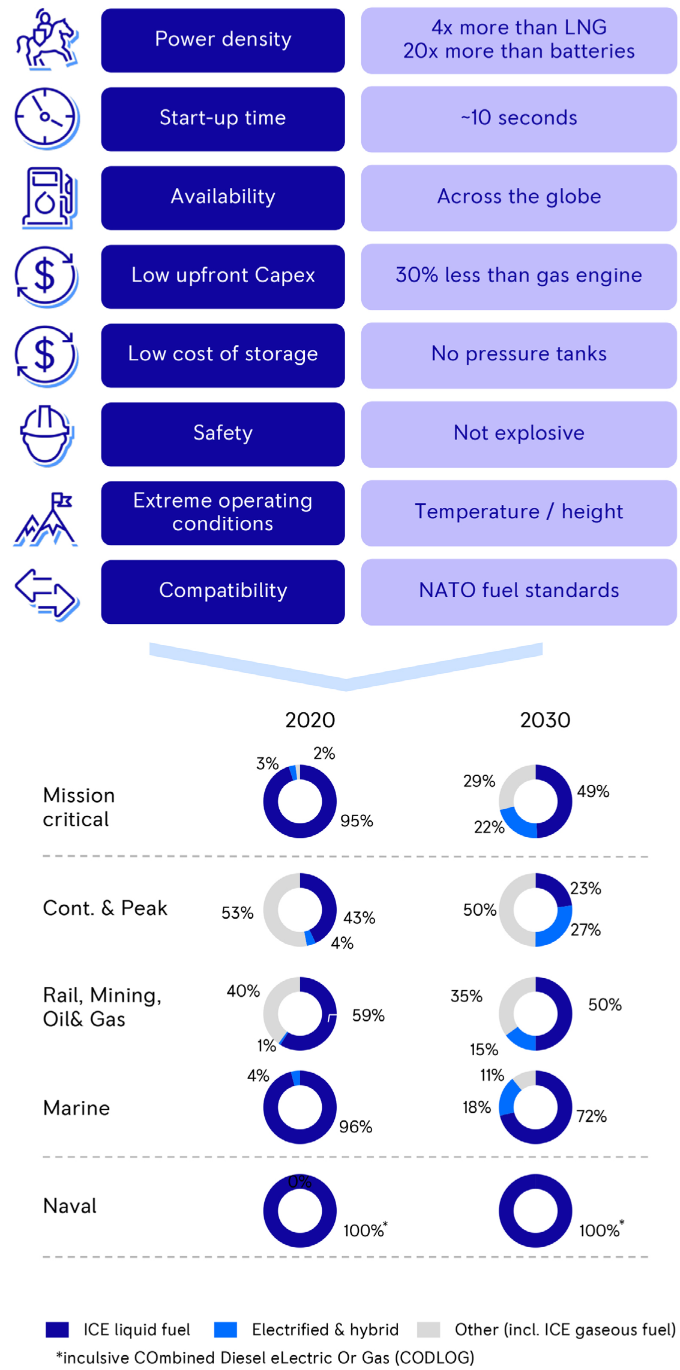


Figure 3
Key buying criteria for ICE liquid fuel (internal source)

Summary and conclusion

Given the world's race to net zero emissions and the important contribution and leverage of our industries, this white paper discussed the expected impact on the core markets of Rolls-Royce Power Systems, and especially on internal combustion engines, mid- and long term.

Today's off-highway market applications in the marine, industrial and power generation sectors are largely dependent on fossil-fuels and contribute a significant amount to GHG emissions. To reach the Paris Agreement goals and to limit global temperature rise to well below 2°C, targeting 1.5°C, a strong development effort into new technologies will be undertaken. We believe that the market will be transformed in a magnitude not seen before to reduce GHG emissions substantially.

We assessed external factors, the specifics of our markets and applications, technology feasibility and deployment viability. This leads us to the conclusion that following a global warming scenario in line with the Paris Agreement, an industry portfolio that used to be based on almost 100% fossil-fired ICE, will turn into one with one third of the applications being electric/hybrid solutions and two third being ICE-based by 2030. The latter will have equal share between sustainable and fossil fuels. However, there are several criteria, foremost the regulatory framework and infrastructure availability, that could either change the balance somewhat or impact the timeline of deployment.

Concluding this expectancy, we see that the ICE principle as such will still play a major role in the market transformation of the coming years and in the net zero future, especially if sustainable fuels will be available as envisioned. However, pure electrical solutions based on battery and fuel cell technologies will be increasingly deployed when/if application requirements can truly be met. To drive emission reduction already in this decade, it is our ambition to push the development of ICE as a bridging technology with use of sustainable fuels, in addition to the development of electrical solutions incl. fuel cell based applications.

For our industries and beyond, it is of utmost importance that the market transformation is driven by a strong commitment of industry aligned with the regulatory bodies and that it is approached with a global, "well-to-wheel" GHG reduction view.

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List of abbreviations

CAPEX	Capital Expenditures
Cont. & Peak	Continuous and peak power generation
CSR	Corporate Social Responsibility
DMU	Diesel Multiple Unit, a multiple-unit train powered by on-board diesel engines
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
HVO	Hydrotreated Vegetable Oils
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
PtX	Power-to-X, conversion of power to other energy carriers (e.g. chemicals)
SBT	Science Based Targets
SCR	Selective Catalytic Reduction
TCO	Total Cost of Ownership

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v Rolls-Royce plc.; Press release; Rolls-Royce puts net zero carbon by 2050 at the heart of future innovation and growth, 17.06.2021 https://www.rolls-royce.com/media/press-releases/2020/05-06-2020-rr-puts-net-zero-carbon-by-2050-at-the-heart-of-future-innovation-and-growth.aspx

vi Ambitious corporate climate action - Science Based Targets - https://sciencebasedtargets.org/

vii Rolls-Royce Power Systems; GHG Target program; Appendix 2

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x North Atlantic Treaty Organization (NATO); Brussels Summit Communiqué - Issued by the Heads of State and Government participating in the meeting of the North Atlantic Council in Brussels; 14 June 2021; Paragraph 6g and 58

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