EARPA Position Paper

Clarification on "ZERO" emissions

About EARPA

Founded in 2002, EARPA is the association of automotive R&D organisations. It brings together the most prominent independent R&D providers in the automotive sector throughout Europe. At present its membership numbers 52, ranging from large and small commercial organisations to national institutes and universities.

SCOPE and OBJECTIVES

Currently many definitions and different viewpoints on zero emissions (ZE) such as "net-zero", "zero tail pipe", "low emissions", "near zero" emissions, etc. are under discussion and treated in different position papers. This paper aims at giving a comprehensive overview on the topic and tries to clarify the meaning of "zero" emissions in different contexts.

Scope:

- Energy production assessment in context of x-to-wheel analyses
- Zero emission in context to vehicle types
- Impact and implications of pollutants (both regulated and non-regulated, primary and secondary) and greenhouse gases (GHG) emissions
- Emission Control and On-Board Monitoring (OBM) to comply with even stricter future regulations for regulated and non-regulated emissions
- Noise and electromagnetic compatibility
- Implications of a widened scope of emissions assessment

Objectives

- Definition of "zero emissions" in terms of a holistic emission level impact assessment
- Highlighting the role of source of energy
- Depicting the side effects of many other substances, VOCs and secondary pollutants
- Estimating non–tailpipe emission like particles from wear, noise and electromagnetic pollution

KPIs and RESEARCH NEEDS

To assess and evaluate "zero emission" the following proposition for a set of KPIs is given, where the main expected impacts can be quantified directly (e.g., CO2 reduction, reduction of number of fatalities, etc.):

- Emission and Life Cycle Analysis leading to the following indexes[1]:
  1. Energy efficiency,
  2. GHG,
  3. Clean Air index,
- Impact on Health of the spread of future technologies,
- Specific assessment of the impact on urban environment of non-tailpipe emissions,
- Sensibility analysis of the relative impact of improving energy and power density on the abovementioned indices.

In the following a rough overview on the research needs for technological developments, especially with transportation vehicles on mind, is given:

[1] A.Damyanov et al., " Green NCAP, Evaluation of the Exhaust Gas Behaviour and the Energy Efficiency of Modern Cars under Demanding Conditions" , Aachen Colloquim, Session Life Cycle Assesment, October 2021

Improvement of basic components

In the last decade emissions of key pollutants in transport sectors decreased significantly in EU-28 while mobility gradually increased [2]. Policy actions at the EU level contributed to that, however, with the new EU roadmap on transportation a huge improvement in emission cut is expected. This requires the development of "near zero" impact powertrains in the medium- and long-term in particular for urban environment operation.

Electrified powertrains and thereon based mission specific hybridisation strategies are a great opportunity to lower pollutant emissions, but their large-scale deployment calls for low cost, lightweight and highly integrated components.

Both EU [3] and US [4] have released roadmaps for minimum achievement for next generation EV components which comprise power densities of traction drives larger than 23kW/L (EU) or 33 kW/L (US) respectively while reducing manufacturing costs to 6 $/kW or €/kW respectively being over 75% reduction in volume and 25% reduction in cost while doubling the target power compared to 2020 goals. A greatly similar increase in power densities and reduction in specific manufacturing costs to the ones before is expected for power electronics by both roadmaps. Further EU roadmap shows a target reduction in the use of rare resources by 60%.

To achieve these targets in a sustainable manner, future assessment of technological developments must be based upon Well-to-Wheel (WtW) emissions and on thorough Life Cycle Analyses (LCA), thus by considering advanced tools, methods and standards. It is essential to adopt a comprehensive approach on powertrain optimization directed at advanced integrated drivetrain concepts which will open new opportunities in vehicle design.

Incorporation of wide bandgap semiconductors (SiC and GaN) with extremely short switching times, new materials, additive manufacturing and optimization technologies will trigger new developments and lead to drastically increased power densities within the drivetrain. Highly efficient fast charging and recuperation technologies combined with predictive control strategies and a higher overall system voltage level pave the way towards ultra-fast charging. But at the same time efforts to overcome side effects such as increased power losses, higher bus communication requirements or greater susceptibility to EMI need to be addressed simultaneously.

Optimization of the energy and power management

For PHEVs a requirement exists to attain short-term zero (tailpipe) emissions to sustain operation within ZE zones, as considered to be initiated from various cities from 2025-2030. To comply with these policies, trusted energy management and associated monitoring technologies will be required to passing these zones and prior to that data/information based control approaches are needed for preparation of the vehicle state (e.g. maximising the battery state-of-charge) and to cope with uncertainty in end-user behaviour. The yet continued development of combustion engines is being explored towards the ZE requirement from a CO2 perspective, including the shift to zero-carbon fuels such as green hydrogen. Research effort still exists in ensuring that these technologies are optimised from a tailpipe perspective towards other pollutant emissions, as well as fugitive (and slip) emissions of hydrogen itself.

FCEV require optimisation of the Balance of Plant, considering available infrastructure and mission profiles. From WtW perspective, methods for the optimisation against hydrogen sources as well as possible plug-in capability are needed.

The focus for BEV will be on optimised drivetrain, thermal and charging management. Coordination of the charging time, frequency, duration and power should be performed holistically for various

[2] Air quality in Europe — 2020 report, EEA Report No 09/2020

[3] Horizon Europe - Work Programme 2021-2022 Climate, Energy and Mobility, Annex 8 Horizon Europe Work Programme 2021-2022 8. Climate, Energy and Mobility

[4] I. Husain et al., "Electric Drive Technology Trends, Challenges, and Opportunities for Future Electric Vehicles," in Proceedings of the IEEE, vol. 109, no. 6, pp. 1039-1059, June 2021, doi: 10.1109/JPROC.2020.3046112

systems-level factors. From a WtW perspective, optimisation to make use of zero-emission energy will be influenced by the time and location of charging.

Developments in the CCAM topic will bring forward several enabling technologies to support zeroing of emissions and which eventually lead to future key research fields for topics of scalable, robust, self-learning energy management systems in combination with improved connectivity, automation, and broader system boundaries. These are covered in other EARPA position papers. On- and offline optimisation, tools and methods need to be developed to ascertain the emission-impact and to assess their impact in a fair manner whether they realise low, zero, or even negative emission potentials. Advances in connectivity and AI technology will provide opportunities to greatly improve the efficiency, reduction pollutant impact and lifetime of new technologies and to deal with limited resources regarding energy management.

Smart Charging, charging strategies

Future charging solutions must consider both external and internal factors of vehicle operation to cover longer range requirements for battery electric mobility implying much larger battery packs, higher charging powers, meaning more demanding charging infrastructure use [5]. These are set to evolve towards 2030 alongside battery technology [6].

Coinciding charging with periods of high availability of renewables supplying power to the grid allows reductions in WtW emissions (even to zero). Shifting the charging to times and locations which allow for lower (or zero) WTW emissions requires solutions both in terms of hardware (e.g. grid-coupled store, bi-directional charging equipment, etc.), as well as holistic control approaches. For higher power-level charging, technologies such as grid-coupled storage is being considered as a means to buffer the energy from the grid. In the use of these technologies, either direct coupling with renewables, or in terms of scheduling of energy transactions with the grid allows for additional degrees of flexibility on making charging zero emission. A systems-level co-design of both charging hardware and control is essential to make vehicles zero emission from a WTW perspective. As before ensuring adoption of standards and interoperability of solutions will remain a pillar of technical developments.

User-centric incentives built around business models, policy measures or enabling ITS solutions will be the key to support these approaches whereas for autonomous and automated vehicles technical solutions around automated charging will be required. To understand the strategies' impact on both vehicles and grid-based storage, extensive knowledge on battery systems must be built reflecting the connection between charging schemes and storage health. Although some approaches already exist, further insight via digital twins (in particular coupled with physics-based models), will facilitate approaches in the trade-off between the use of batteries in charging schemes and the potential negative impacts on health.

Electromagnetic compatibility

Electric machines and electric and hybrid vehicles generate electromagnetic interference (EMI) during operation, which affects the surrounding environment and other electronic devices. Their main sources in EVs are the fast-switching power electronics (inverters, converters and chargers), the motors and signal coupling between different voltage level cabling. EMI can cause disturbances to the normal operation of other nearby electronics equipment like electronic braking system, antilock braking system and navigator, thus is directly related to vehicle safety. Even though dealing with EMI is covered by regulations for electromagnetic compatibility the automotive industry struggles to align EMI with the required efficiency improvements established by the roadmaps for the development of next gen EV components [7].

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[5] European Roadmap Electrification of Road Transport, ERTRAC, June 2017

[6] Batteries Europe Strategic Research Agenda, December 2020 https://ec.europa.eu/energy/topics/technology-and-innovation/batteries-europe/news-articles-and-publications/sra_en

[7] European Roadmap Electrification of Road Transport, 3rd Edition, Version: 10 Date: June 2017

New wide-bandgap power devices enable the transition to automotive HV levels of 1000V and above which in turn is resulting in lower conduction losses and power electronics downsize. On the other hand, the outcome of higher possible switching frequencies is higher EMI levels and a higher overall HV level will increase the amplitude of EMI and trigger a shift of the main interference to high frequency bands [8]. The latter may impose issues to the public power grid as interference from the vehicle charger can propagate through charging infrastructure to external electromagnetic environment. Inversely the vehicle must withstand EMI from the outside to ensure charging safety.

To achieve the requested efficiency, future EMI containing measures must comprise innovative multilevel converter architecture layouts along the adoption of new materials for common mode chokes to properly filter disturbances at higher frequencies [9].

Future of internal combustion engines

From a Well-to-Wheel perspective an internal combustion engine that runs on renewable fuels – i.e., sustainable bio or e-fuels - is basically just as CO2-neutral as an EV using renewable electricity in operation and production. Global CO2 emissions doesn't solely depend on drivetrain technology but also on the choice of the energy source. So, in a life cycle analysis that goes beyond the vehicle's service life, an ICE vehicle may even perform better than vehicles with other propulsion systems. Moreover, renewable fuels could contribute to maintaining a sustainable market situation for existing fleets in resale and support social balance by preventing bans on internal combustion engines.

The EU climate targets are especially hard to reach for the transport sector where trucks serve as backbone of trade and commerce in Europe [10] and over 98% of them are operated with Diesel [11]. Replacement by electric vehicles is seldom possible by the current state of technology which is why an increased use of renewable fuels is supporting. Hydrogen has the potential to significantly contribute towards WtW and life-cycle CO2 neutral mobility. Furthermore the application of hydrogen internal combustion engines allow existing manufacturing structures, robustness, low demands on fuel quality and a much more favourable cost situation, which could lead to a much faster penetration and development of the starting infrastructure limiting the drawbacks to the application of de-NOx systems like using urea-based selective catalytic reduction like in modern diesel engine exhaust aftertreatments.

Extended testing conditions and pollutants consideration

Current on-road (RDE) testing boundaries do not sufficiently cover the spectrum of operating conditions experienced in daily driving, hence real-world emissions may considerably deviate. To overcome this issue the following conditions should be considered in future testing procedures:

- Low ambient temperature and cold start for short trips opposed to the range of current driving cycles to assess the impact of the cold-start effect.
- Driving under high engine load as happens for harsh accelerations, uphill driving, trailer pulling or at high vehicle speeds.
- Idling and low engine load operation that may occur during traffic congestion or stop-and-go situations.
- The state of the DPF to differentiate between a "fresh" (clean) state of the filter and regeneration.
- Extended vehicle mileage above the current limits.

[8] J. Hu, X. Xu, D. Cao and G. Liu, "Analysis and optimization of electromagnetic compatibility for electric vehicles," in IEEE Electromagnetic Compatibility Magazine, vol. 8, no. 4, pp. 50-55, 4th Quarter 2019, doi: 10.1109/MEMC.2019.8985599

[9] Concari, L., Barater, D., Toscani, A., Concari, C., Franceschini, G., Buticchi, G., Liserre, M., Zhang, H. "Assessment of efficiency and reliability of wide band-gap based H8 inverter in electric vehicle applications" Energies, 2019, 12(10), 1922

[10] https://www.acea.be/uploads/publications/ACEA_CV_manifesto_2019-2024.pdf#page=3

[11] https://www.acea.be/uploads/publications/ACEA_10-point_plan_European_Green_Deal.pdf

Further to the currently regulated pollutants, additional types should be considered in the future which can roughly be subdivided into two categories:

- Pollutants with impact of air quality such as NO_2, NH_3 (formed in the TWC), HCHO (formaldehyde), NMOG (fuels with high alcohol content), PN_{10}, total PN, secondary particles, evaporative emissions, brake and tyre particles (also relevant for BEVs), C_2H_4O (acetaldehyde), ethanol, isocyanic acid, O_3, toluene, benzene, etc.
- Pollutants that act as GHGs such as N_2O (formed in the SCR) and CH_4 (for NG vehicles that need a very dedicated λ-control).

Above conditions will yield optimized and new emission control technologies which go beyond the emission abatement and carefully consider any side effects, such as CO_2 penalties in addition. At the same time, the requirement to include the extra pollutants may boost the use of alternative fuels such as hydrogen or e-fuels.

Twinning of regulations

All worldwide regulations are strongly committed to reducing pollutant emissions and global warming effect due to greenhouse gases. In twinning the international regulation systems, we will consider mainly USA and EU regulations as both provide bases for others (e.g., South Korea - US; Japan, China, India - EU; all with adaptions to their countries requirements). The differences from EU to US regulations are that:

- US requires measurement of HCHO and limits NMOG and NOx, whereby NMOG can be determined by measurement or calculation.
- Evaporative emission requirements are more extensive in US than in EU and demand high temperature vehicle driving and measurement of HC emissions and certification of on-board refuelling vapor recovery (ORVR), refuelling spit-back and canister bleed emissions in a 3-day diurnal (2-day in EU).
- US implements a driving cycle to assess the influence of A/C and solar radiation on consumption and pollutant emissions, and a second aggressive one to evaluate high engine load effects.
- Further, OBD has more stringent requirements for demanding failure tests

A separate global warming score for each vehicle based on its greenhouse gas emissions (N2O, CH4 and CO2) from operation and fuel production is provided by the CARB EP label [12].

Brazil has similar requirements towards HCHO, NMOG, NOx, measurement and limit of Aldehydes as US regulation does, with the difference that the determination of NMOG can be done by calculation or with the measurement of NMHC, aldehydes, ketones and ethanol. Further, measurement (no limit) and declaration of NH3 will be mandatory as well as the adoption of more stringent evaporative emission requirements like the one in the US.

[12] California Air Resources Board (CARB) Environmental Performance (EP)

Cyber Security

Detected issues due to the vulnerability of emission control systems and fuel efficiency relevant systems from being remotely accessed and influenced resulting in excessively high emissions and / or fuel / energy consumption. The issue is real and known [13,14,15]:

- Vehicles security at control unit level is low or even not given - Security by obscurity.
- The deactivation of the exhaust aftertreatment (e.g., SCR system) is very easily possible and the cost for doing so is rather low (~100 €).
- In contrast to that the cost of AdBlue for trucks and HD-vehicles sums up to around 2000 €/a.

Hauling / Freight companies operate at very low margins of ~2%. With the yearly costs of 20 k€ per truck, 100 k€ for personnel, 20 k€ for fuel and 10 k€ for service the profit is about 3000 €. By manipulation of the exhaust aftertreatment system this profit could be raised to 5000 €.

Methods for checking for or proving manipulation of the aftertreatment system could be based upon measurement of concentrations and ratios of NOx/CO2 behind the vehicle in question. Work in this direction is already being established [16].

Mass and volume impact

Two paths of interest can be identified regarding mass and volume impact of future energy sources, BEVs with focus laid on 3rd and 4th gen. batteries and FC vehicles with focus laid on tank systems.

Focus for **batteries** [17,18] lies on the development of advanced materials for cathodes, anodes and electrolytes to targeted energy densities up to 400 Wh/kg or 1000 Wh/l at cell level, to sustain up to 3000 charging cycles and operating voltages beyond 4.7 V at cell level for Gen. 3 batteries. For Gen. 4 batteries the focus of development is on solid-state electrolytes as well as cathode and anode materials enabling higher thermal and electrochemical stability while targeting energy densities of 400-500 Wh/kg and 800-1000 Wh/l at cell level, fast charging at rates of 3-5C, cyclability up to 3000 charging cycles and improved safety.

For automotive **Hydrogen** applications the roadmap of necessary developments focuses on compensating for hydrogen's low volumetric energy density by advanced storage methods [19] that allow for energy densities of 1.8 kWh/kg or 1.3 kWh/l until the year 2025 and 2.2 kWh/kg or 1.7 kWh/l respectively for the following years.

Acceptance and participation of the population

The European Green Deal recently announced that to protect Europe's citizens and ecosystems it is necessary to move towards a zero-pollution ambition, and better prevent and remedy pollution from air, water, soil, and consumer products. This transition is strongly relying on electrification and the public opinion to carry it, as it will substantially differ from fossil-sourced transportation structures in terms of costs, usage characteristics and environmental effects. Hence clear and transparent information and communication is key to mitigate change-aversion.

Also, industry leaders and policy makers benefit from this approach as they need educated actions to rightfully impact through decision focusing in the long-run social benefit, beyond any technical or political trend. A complete lifecycle analysis comprising among others energy production mix,

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[13] https://www.parlament.gv.at/PAKT/VHG/XXV/AB/AB_11012/imfname_624494.pdf

[14] https://www.youtube.com/watch?v=SfE2AwoPJhM

[15] https://www.uni-heidelberg.de/studium/journal/2016/01/stickoxide.html

[16] https://www.researchgate.net/publication/334043955_The_ICAD_iterative_cavity-enhanced_DOAS_method

[17] https://ec.europa.eu/energy/topics/technology-and-innovation/batteries-europe/news-articles-and-publications/sra_en

[18] Horizon Europe - Work Programme 2021-2022 Climate, Energy and Mobility, Annex 8 Horizon Europe Work Programme 2021-2022 8. Climate, Energy and Mobility

[19] https://www.energy.gov/eere/fuelcells/doe-technical-targets-onboard-hydrogen-storage-light-duty-vehicles

transport losses and recycling steps must evaluate the cost to the environment. Given the interdependency of different industries and players to make transportation truly sustainable, local use cases should be regarded independently, and intermediate solutions proposed bespoke according to needs and resources available. Joint effort in the development of the analysis, implementation and communicating tools is needed to produce truly sustainable including solutions and frameworks for the population to willingly embrace the transition towards zero-pollution.

For further information, please contact our contact persons of the Foresight Group: Energy, Powertrains and Electrification

Contact

FG EPE Speaker
Bernhard Brandstätter
E: bernhard.brandstaetter@v2c2.at

FG EPE Secretary
Marco Mammetti
E: marco.mammetti@idiada.com

Drafting:

Marco Mammetti (IDIADA), Guillem Badia (IDIADA), Michael Nöst (IESTA), Alois Danninger (AVL), Athanasios Dimaratos (LAT), Zissis Samaras (LAT), Steven Wilkins (TNO) and Davide Barater (UNIMORE)

More information at our website: www.earpa.eu