

OUTCOMES OF THE STAKEHOLDER WORKSHOP

Online 13 November 2023



Funded by
the European Union

WORKSHOP PROGRAM

13:00 – 14:00 Introduction block

- Introduction to the workshop (*Pedro Gomes, POLIS network*)
- Overarching and sectorial challenges of aviation, shipping, heavy-duty road transport and non-road mobile machinery, the hard-to-electrify transport sectors (*Miikka Dal Maso, Tampere university, REALCHEM coordinator*)
- Technology trajectories for HtE transport sectors to year 2050 (*Erik Fridell, IVL*)
- Mitigation strategies and technology packages (*Niina Kuittinen, VTT*)

14:00 – 15:10 Break-out session on the 3 transport sectors

Aviation (*Moderator: Louise Ganeau, rapporteur: Jana Moldanova*)

Shipping (*Moderator: Georgios Tsakonas, rapporteur: Volker Matthias*)

HDV & working machinery (*Moderator: Niina Kuittinen, rapporteur: Miikka Dal Maso*)

- Presentation round
- Sector-specific introduction
- Discussion of questions (Technological trajectories, Mitigation strategies, Stakeholder needs regarding the technological packages)

15:10 – 15:20 Break

15:20 – 16:00 Wrap-up session (*Moderator: Erik Fridell*)

- Summary of the discussions in the break-out rooms by rapporteurs
- Final discussion
- Conclusions, further steps (*Miikka Dal Maso*)

Legal Disclaimer

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101192395. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor CINEA can be held responsible for them.

TABLE OF CONTENTS

Workshop program	I
TABLE OF CONTENTS	II
1 Introduction	1
2 Outcomes of the Shipping break-out session	1
2.1 Technological Trajectories	1
2.2 Technology drivers	3
2.3 Challenges and concerns	6
2.4 Workshop inputs on expectations, needs, and recommendations for shipping technology packages	7
3 Outcomes of the HDV and non-road mobile machinery break-out session	9
3.1 Expected technological trajectories	9
3.2 Technology drivers	10
3.2.1 Diesel type fuels (biogenic, synthetic)	10
3.2.2 Alcohols (methanol, ethanol)	10
3.2.3 Gaseous fuels (biomethane, hydrogen)	11
3.2.4 Hydrogen	11
3.2.5 Ammonia	11
3.2.6 Fuel cells, electrification	11
3.3 Milestones and barriers	12
3.4 Summary	13
4 Outcomes of the Aviation break-out session	13
4.1 Estimate of absorption of alternative energy carriers, energy efficiency and transport work in the sector in 2030 and 2050	13
4.2 Discussion on regulatory framework and technological developments	15
4.3 Technology drivers	16
4.4 Major milestones and biggest barriers and risk concerns for the new fuels and technologies	17
4.5 Stakeholders' expectations, needs and recommendations for the Technology Packages	18
4.6 Conclusions from the aviation session	18
5 Final remark	18

The REALCHEM project aims to promote a clean and climate-friendly transport system by studying emissions from low carbon fuels in hard-to-electrify (HtE) transport sectors, including aviation, shipping, and heavy-duty on-road and non-road mobile machinery. The project will observe emissions from various fuels and engines under real-life conditions, model their effects on air quality and human health, and focus on the most important new technologies. REALCHEM will use a large amount of pre-existing data on both low-carbon and fossil fuels and conduct novel experimental work in all three HtE transport modes. The aim is to produce guidance and technology packages for cleaner transport in terms of health effects and climate impacts. The data will be organized into a low-carbon fuel emission database, which will help REALCHEM generate new knowledge and identify the most efficient new fuels and technologies.

The project has three main objectives:

1. Produce robust, comprehensive, and actionable scientific data on the characteristics of emissions from low-carbon fuels in the Hard-to-Electrify transport modes.
2. Understand the effect of introducing low-carbon fuels to the developing technology matrix on human health, climate, and the environment:
3. Help technology developers and users to understand the emission formation and reduce the harmful pollution from engines using low-carbon fuels.

These efforts are in line with Europe's ambitious climate targets, the Green Deal, and the vision of zero pollution by 2050. The need for combustion-based technologies in heavy-duty transport, non-road machinery, shipping, and aviation sectors remains, and the decarbonisation of these sectors is expected to be driven by a shift from fossil fuels to low-carbon alternatives. This will lead to changes in combustion technologies and air pollutant emissions. REALCHEM will provide scientific evidence and recommendations to navigate this changing future.

Social Media links:



@REALCHEM-project



@REALCHEM-project

For further information please visit WWW.REALCHEMPROJECT.EU

1 INTRODUCTION

This document summarises outcomes of the Stakeholder workshop held online 13 November 2025. Aim of the workshop was to get input from the stakeholder community associated with the project regarding future development of the hard-to-electrify transport sectors, i.e. heavy-duty, non-road mobile machinery, shipping and aviation in terms of adaptation of alternative fuels, emission abatements and new propulsion technologies. Also needs and expectations of the stakeholders on the project results have been discussed.

During the first block of the workshop, the project and the themes were introduced by the project coordinator Miikka Dal Maso, Tampere university, Erik Fridell, IVL, and Niina Kuittinen, VTT. Each break-out session was introduced by technological trajectories in context of air quality concerns for the respective sector by the session chairs (Georgios Tsakonas: Shipping, Niina Kuittinen: HDV & NRMM, Louise Ganeau: Aviation). Slides accompanying the presentations can be found [here](#).

The second block of the workshop took place in three break-out sessions for 1. HDV and non-road working machinery, 2. Shipping and 3. Aviation, where attendees discussed and worked online in areas with questionnaires and diagrams prepared in Canva. Results of this work in form of the Canva board from the break-out sessions can be seen here: [CANVA BOARD](#).

2 OUTCOMES OF THE SHIPPING BREAK-OUT SESSION

Moderator: *Georgios Tsakonas*,

Rapporteur: *Volker Matthias*

Participants: External stakeholders with expertise in shipping and shipping fuels, REALCHEM members.

2.1 Technological Trajectories

As part of the workshop activities, participants were invited to express their perspectives on future shipping pathways through two complementary exercises. In the first activity, participants indicated their expectations regarding the contribution of different propulsion technologies to the overall technology mix by placing a dot on the corresponding charts for the years 2030 and 2050. In parallel, a second activity focused on the participants' views on future energy efficiency improvements and the share of the fleet expected to achieve carbon neutrality by 2030 and 2050. To allow for a comparison between perspectives, differently coloured dots were used for stakeholders and REALCHEM members. The aggregated results of these activities are presented in Figures 2.1–2.3.

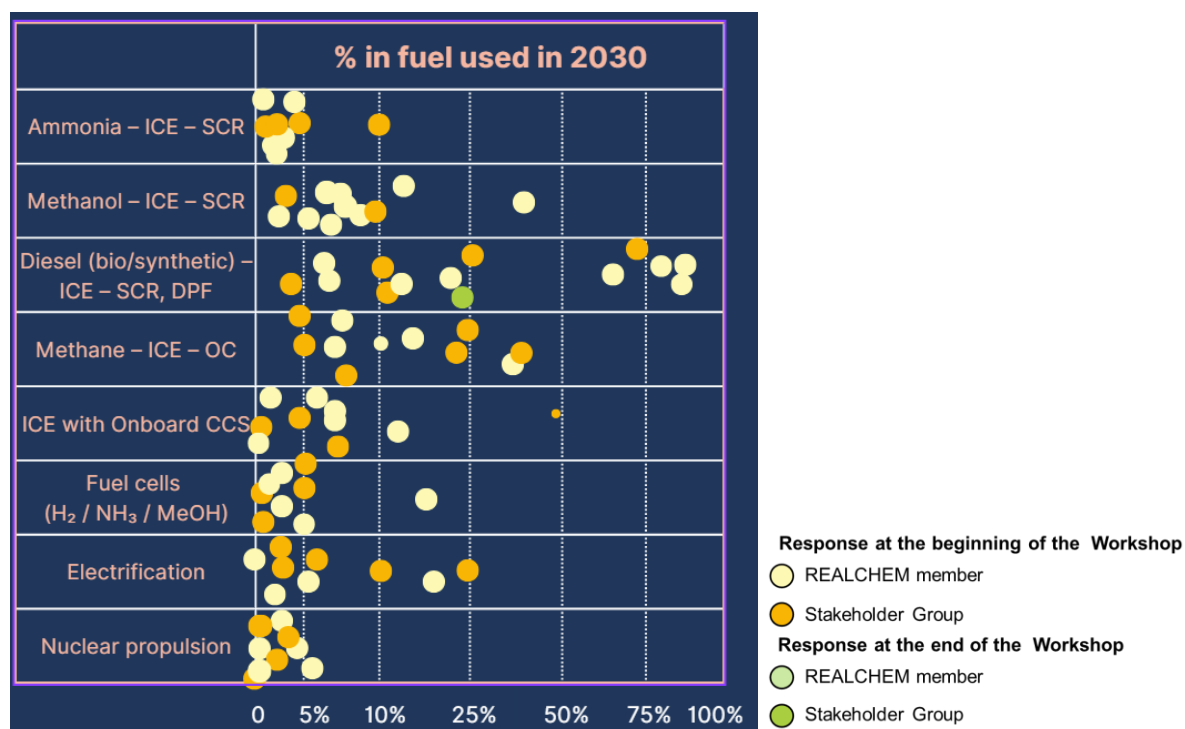


Figure 2.1 Perceived contribution of shipping fuels in 2030 as indicated by stakeholders and REALCHEM members

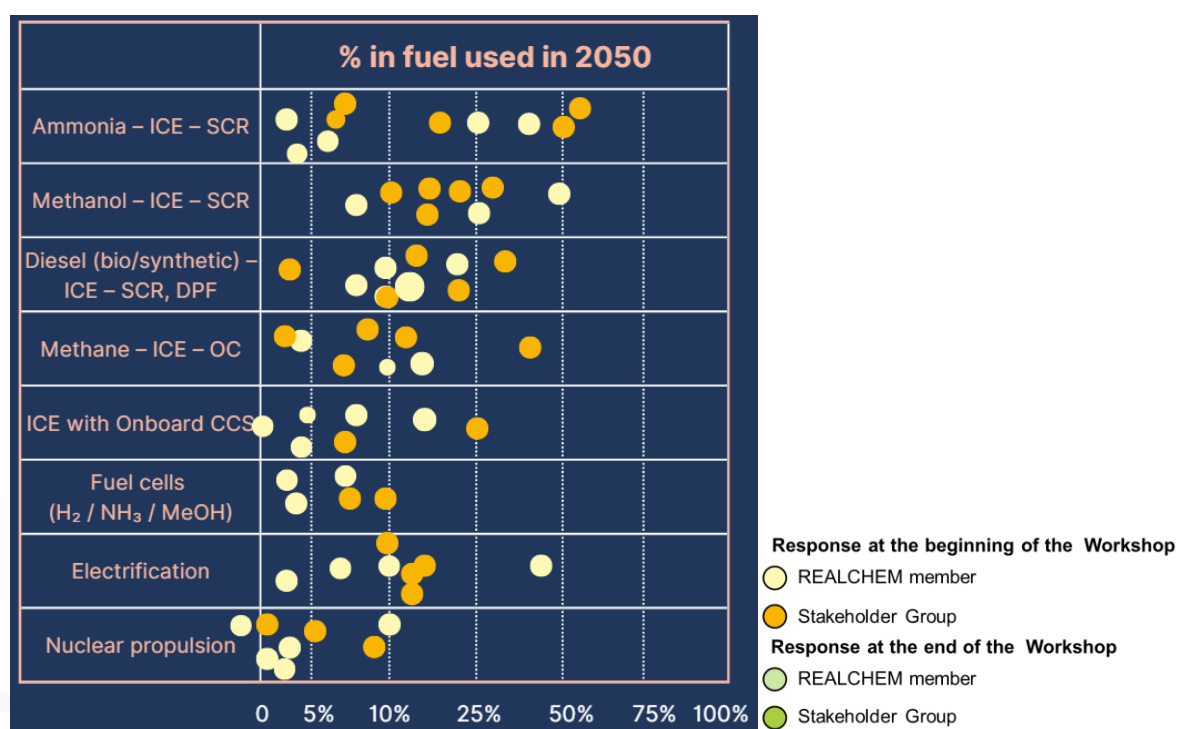


Figure 2.2 Perceived contribution of shipping fuels in 2050 as indicated by stakeholders and REALCHEM members

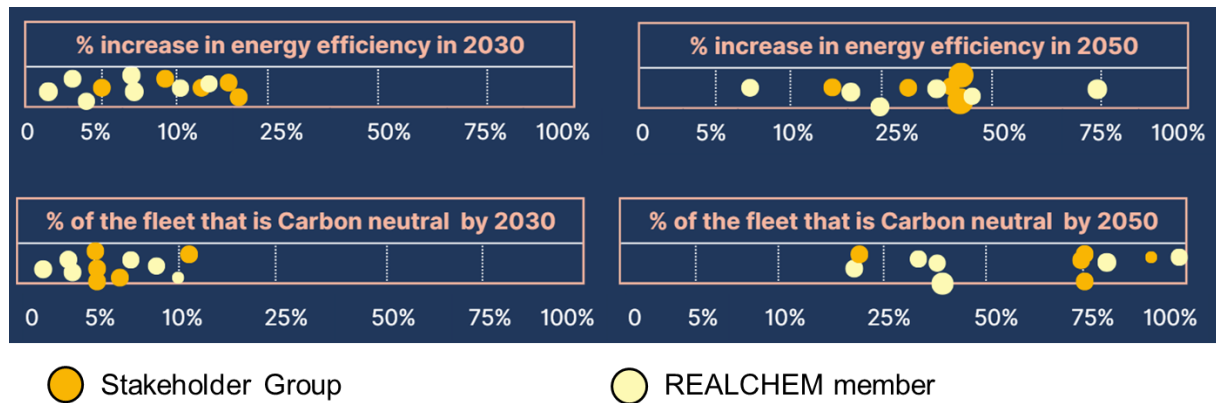


Figure 2.3 Perceived energy efficiency improvements and carbon-neutral fleet share in 2030 and 2050 as indicated by stakeholders and REALCHEM members

The results indicate a strong convergence of views between REALCHEM members and stakeholders regarding the pace and nature of the shipping transition. Overall, participants agreed that 2030 is too early to expect a large-scale transition to alternative fuels, with expectations for both fuel shares and energy efficiency improvements remaining relatively modest in the near term. The distribution of responses further suggests that no single technology is perceived as a standalone solution, reinforcing the view that the decarbonisation challenge must be addressed through a combination of technologies and measures. Looking further ahead, participants expressed significantly higher expectations for 2050, pointing towards a future shipping sector characterised by a diverse mix of propulsion technologies, rather than dominance by one option. Finally, although participants were given the opportunity to indicate a change in perspective after the workshop using green dots, very few such markers were used, suggesting that participants' views remained largely stable before and after the discussions.

2.2 Technology drivers

Next, participants were asked to identify the key drivers influencing the choice of future shipping technologies for both deep-sea and short-sea shipping. A structured table covering a range of propulsion options was provided, and participants were invited to place sticky notes summarising their views. Different colours were used to distinguish participant groups, with green notes representing stakeholders and yellow notes representing REALCHEM members. The results of this exercise are presented in Figure 2.4.

Technology drivers

What are the drivers (policy instruments, technology maturity, fuel production pathways, costs, required aftertreatment) for you to choose a future technology

Place your sticky notes in the tables

	Deep-sea shipping	Short-sea shipping
Ammonia – ICE – SCR	Technology maturity Regulation and Price projections Price and Regulation Might be easy to produce	Low volumetric energy for deep-sea shipping
Methanol – ICE – SCR	Technology maturity Regulation and Price projections Price and Regulation High availability already in use, no new technologies Technology maturity - FuelEU Maritime Maturity, EUETS not enough, can use biomass of lower quality. Storage, blending. - requires carbon, which in turn requires more energy for air capture than for example N in ammonia, N2O emissions.	much easier to handle compared to LNG and Ammonia technology readiness
Diesel (bio/synthetic) – ICE – SCR, DPF	technology maturity Regulation and Price projections Price and Regulation no technical changes needed - low risk approach Diesel will remain in the global fuel mix	technology readiness
Methane – ICE – OC	FuelEU ETS incentivises LNG Methane slip and related legislation could increase operational cost. Technology maturity will reduce CH4 slip. Greater environmental and climate benefits Regulation (EU, IMO), cost, fuel availability, technology for methane slip reduction - FuelEU Maritime Maturity, EUETS not enough, can use biomass of lower quality. Storage. - requires carbon, which in turn requires more energy for air capture than for example N in ammonia.	FuelEU and ETS incentivises LNG
ICE with Onboard CCS	Technology maturity Technology will evolve and CO2 supply chain will grow possibly not so easy way to reduce CO2	
Fuel cells (H₂ / NH₃ / MeOH)		could be favourable for the direct use of hydrogen because the volumes needed are low H₂ or NH₃ require frequent bunkering
Electrification	Low volumetric energy capacity	Battery technology developments CPS requiring Regulations large batteries are available, some ships already run on electricity on short distances More frequent battery charging *Energy efficient, in a few cases low cost depending on battery size... *charging problem, storage space, cost of batteries, materials...
Nuclear propulsion	Clean tech. Needs policy instruments Proven technology in naval shipping	

REALCHEM member

Stakeholder Group

Figure 2.4 Technology drivers for future shipping technologies as identified by stakeholders and REALCHEM members

For clarity, the inputs provided during the workshop activity are listed below in text form. Green bullet points denote input from stakeholders, yellow bullet points denote input from REALCHEM members:

Ammonia – ICE - SCR:

Deep-sea shipping:

- Technology maturity
- Regulation and price projections
- Price and regulation
- Might be easy to produce

Short-sea shipping:

- *Low volumetric energy density for deep-sea shipping*

Methanol – ICE – SCR:**Deep-sea shipping**

- *Maturity and bunkering availability*
- *Technical readiness of engines*
- *High availability*
- *Already in use, no new technologies*
- *Technology maturity*

Short-sea shipping

- *Much easier to handle compared to LNG and ammonia*
- *Technology readiness*

Both

- *+FuelEU, Maritime Mature, EU ETS (not enough), can use biomass of lower quality. Storage. Handling.*
- *Requires carbon, which in turn requires more energy for air capture than for example in ammonia. NOx emissions.*

Diesel (bio/synthetic) – ICE – SCR, DPF:**Deep-sea shipping**

- *Misassumption on scalability / good lobby work*
- *Diesel will remain in the global fuel mix*
- *No technical changes needed – low risk approach*

Short-sea shipping

- *Technology readiness*

ICE with Onboard CCS:**Deep-sea shipping**

- *Possibly not so costly way to reduce CO₂*
- *Technology will evolve and CO₂ supply chain will grow*

Fuel cells (H₂ / NH₃ / MeOH):

Deep-sea shipping

- *Could be favourable for short-sea due to hydrogen because the volumes needed are low*
- *H₂ or NH₃ require frequent bunkering*

Electrification:

Deep-sea shipping

- *Low volumetric energy capacity*

Short-sea shipping

- *Battery technology development*
- *OPS requiring regulations*
- *Large batteries are available, some ships already run on electricity on short distances*
- *More frequent battery charging*
- *+Energy efficient, in a few cases*
- *Low cost (depending on battery size)*
- *Charging problem, storage space, cost of batteries, minerals*

Nuclear propulsion:

- *Clean tech – needs policy instrumentations*
- *Proven technology in naval shipping*

The outcomes of the technology drivers activity indicate that technology maturity and readiness are the dominant factors influencing future shipping technology choices, with a clear preference for solutions that are already in use or require minimal modifications to existing systems. Policy and regulatory instruments are repeatedly identified as key drivers, particularly for options such as onboard CCS, nuclear propulsion, methane-based technologies, and alternative fuels. At the same time, operational constraints, including energy density, storage volume, and bunkering or charging frequency, clearly differentiate deep-sea and short-sea shipping, leading to distinct technology pathways for each segment. While deep-sea shipping remains constrained by energy density and long-range operational requirements, short-sea shipping allows greater flexibility, enabling the consideration of electrification, fuel cells, and alternative fuels where operational conditions permit. Across all options, cost and supply chain considerations, such as fuel availability, CO₂ supply chains, and battery requirements, emerge as critical drivers influencing both the feasibility and scalability of future technologies.

2.3 Challenges and concerns

In this activity, the participants were asked to identify the main challenges and concerns associated with different decarbonisation options for shipping. A structured table was provided, listing a range of

propulsion technologies and potential challenge categories. The participants were invited to place dots or sticky notes to indicate which issues they considered most relevant for each option. The results of this exercise are presented in Figure 2.5.

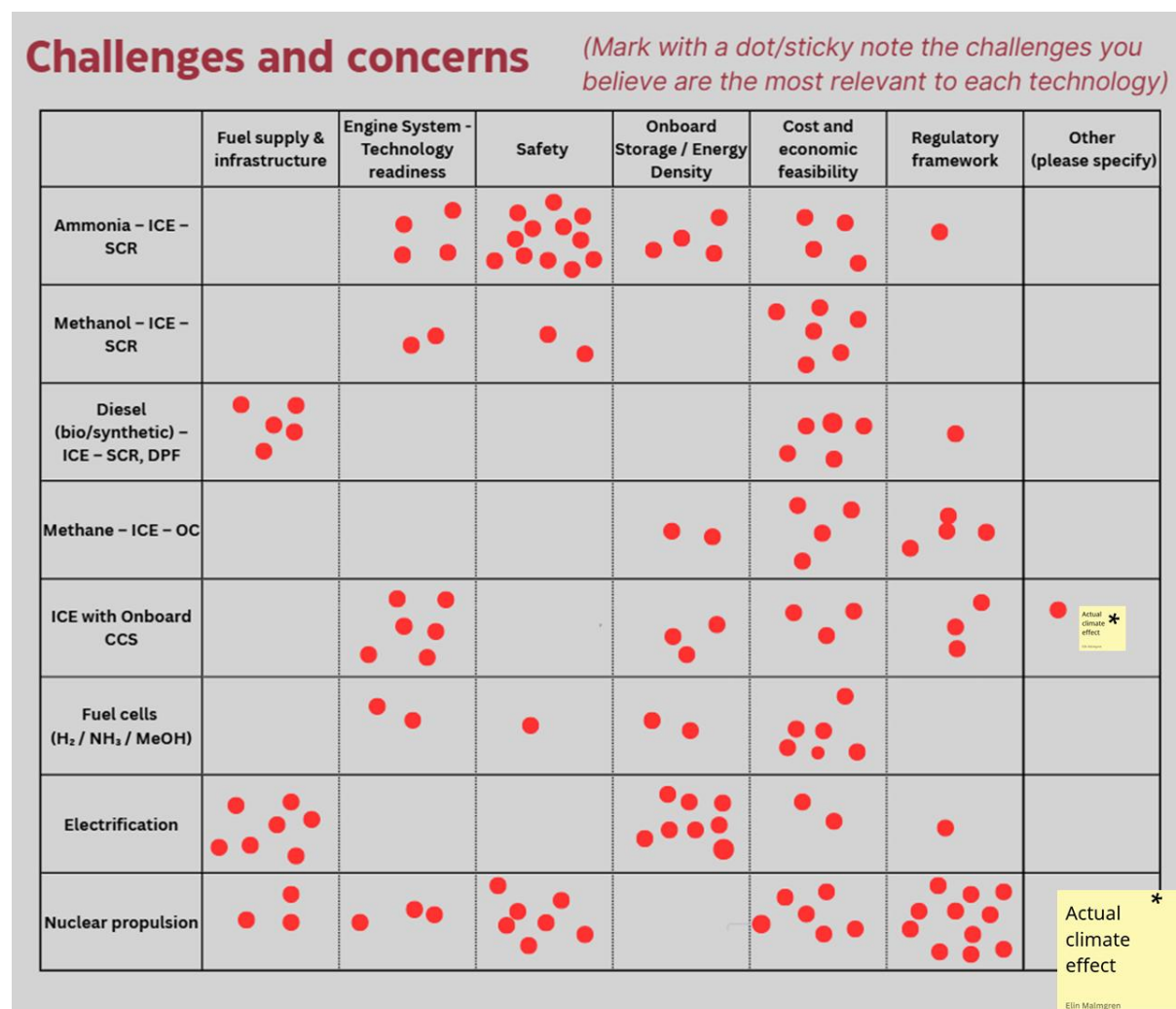


Figure 2.5 Challenges and concerns for shipping decarbonisation options as identified by workshop participants

The results of the Challenges and Concerns activity show that cost and economic feasibility are key concerns for almost all technologies. In addition, safety considerations and limitations on on-board storage or energy density emerge as significant barriers, particularly for alternative fuel options. Overall, the findings show that no technology is free from challenges, highlighting the need for the parallel development of multiple decarbonisation options for shipping.

2.4 Workshop inputs on expectations, needs, and recommendations for shipping technology packages

In this activity, participants were invited to share their expectations, needs and recommendations regarding the development and implementation of technology packages for shipping. An open board is provided and participants place sticky notes to highlight priority issues, research needs, regulatory parameters and broader recommendations. The outcome of this activity is presented in Figure 2.6.

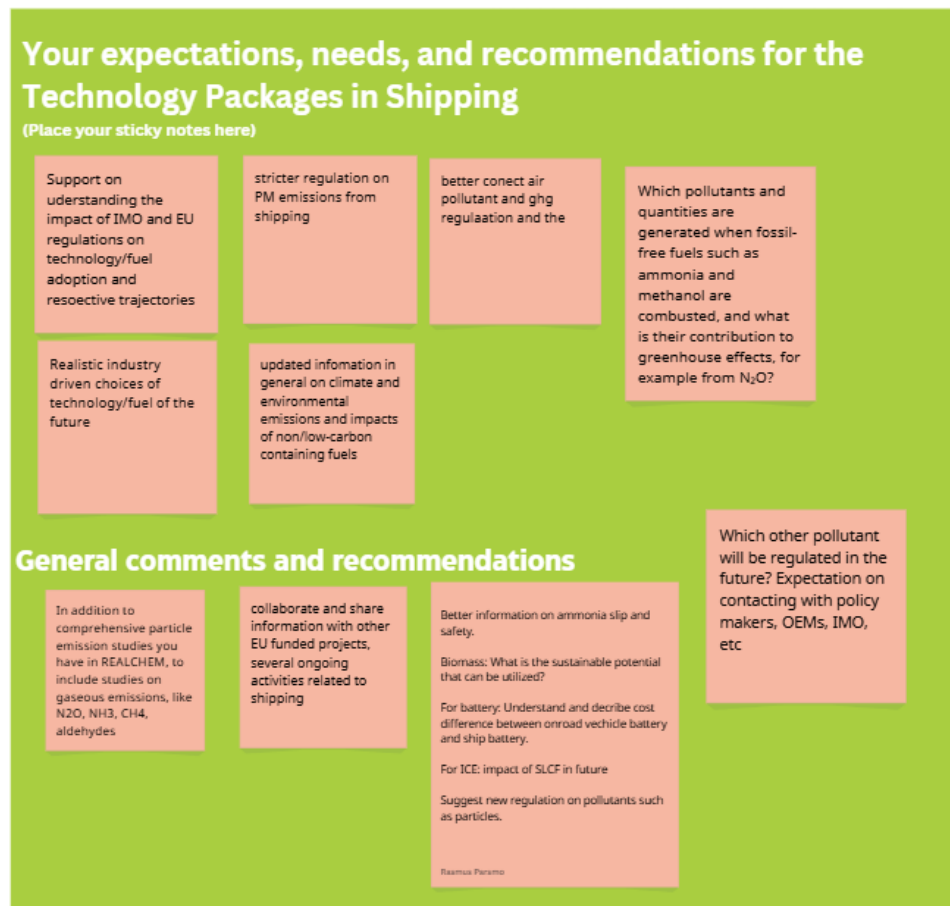


Figure 2.6 Participants' expectations, needs, and recommendations for REALCHEM shipping technology packages

For clarity, the inputs provided during the workshop activity are listed below in text form:

- *Support on understanding the impact of IMO and EU regulations on technology/fuel adoption and respective trajectories*
- *Stricter regulation on PM emissions from shipping*
- *Better connect air pollutant and GHG regulation*
- *Which pollutants and quantities are generated when fossil-free fuels such as ammonia and methanol are combusted, and what is their contribution to greenhouse effects, for example from N₂O?*
- *Updated information in general on climate and environmental emissions and impacts of non/low-carbon containing fuels*
- *Realistic industry driven choices of technology/fuel of the future*
- *In addition to comprehensive particle emission studies you have in REALCHEM, to include studies on gaseous emissions, like N₂O, NH₃, CH₄, aldehydes*
- *Collaborate and share information with other EU funded projects, several ongoing activities related to shipping*
- *Better information on ammonia slip and safety.
Biomass: What is the sustainable potential that can be utilized?
For battery: Understand and describe cost difference between on-road vehicle battery and ship battery.
For ICE: impact of SLCF in future*
- *Suggest new regulation on pollutants such as particles*

- Which other pollutant will be regulated in the future? Expectation on contacting with policy makers, OEMs, IMO, etc

3 OUTCOMES OF THE HDV AND NON-ROAD MOBILE MACHINERY BREAK-OUT SESSION

Moderator: Niina Kuittinen,

Rapporteur: Miikka Dal Maso

Participants: 3 stakeholder representatives, 3 REALCHEM consortium members

3.1 Expected technological trajectories

The breakout session was started by an introduction to some viewpoints inspired by the ongoing REALCHEM literature review by Niina Kuittinen. As the first task, the participants were invited to discuss the main fuels they expect to be used in the HD and NRMM sectors in the near (2030) and further (2050) future, separately for each of the two sectors. The results are presented in Figure 3-1, below.

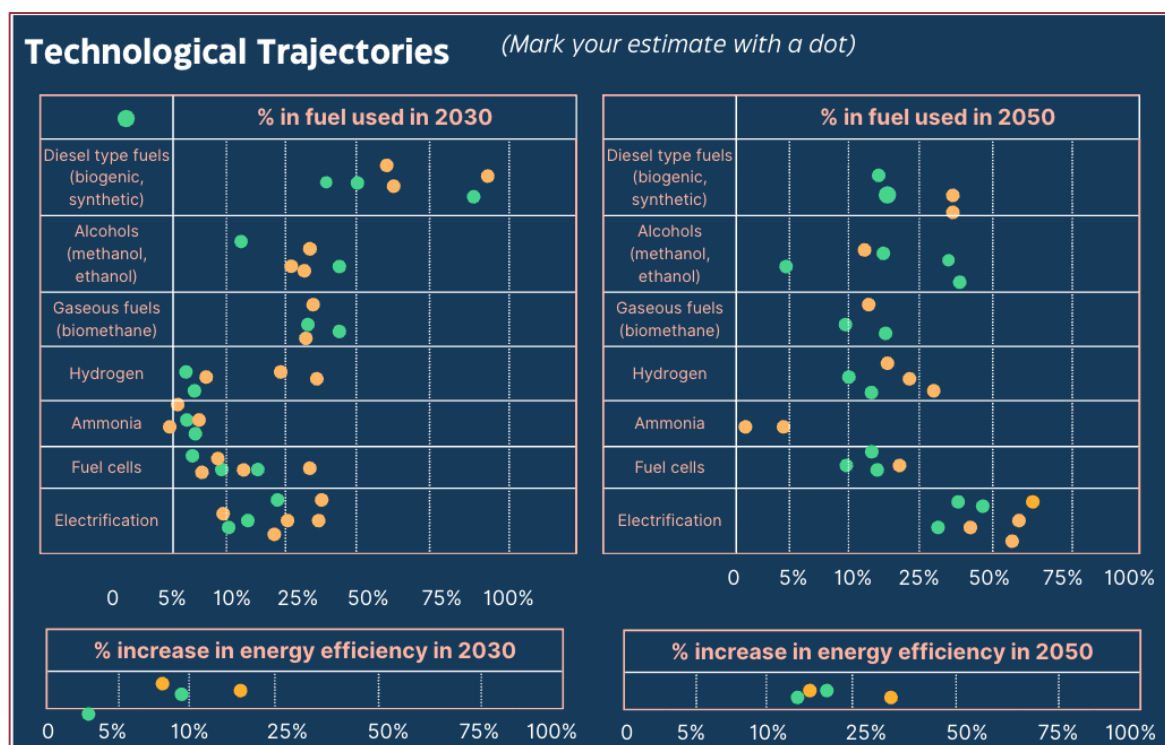


Figure 3-1 Breakout results for expected market shares for heavy duty (HD ●) and non-road mobile machines (NRMM ●) within the ND&NRMM stakeholder group.

The results among the stakeholders were fairly convergent, with the largest variation in the expected market share of diesel-type fuels for non-road mobile machines. In the short term, drop-in diesel-type fuels were seen as the dominating fuel in the market (>75% of the market), with alcohols and gaseous fuels making up the rest of the market and electrification gaining ground but remaining at ca 25% of the total market for HDVs and 15% for NRMM. In the longer term, the market outlook is dominated by the advancing electrification, with electricity-based technologies covering half of the market. The non-electrified market is more varied in terms of fuels expected, with approximately equal expected shares

of alternative fuels and technologies, with the exception of ammonia which is not seen as a viable option even in the longer term.

Potential gains in efficiency are seen to be in the range of 5-10% in the short term and 10-25% in the longer-term; in the discussion, the efficiency gain in the short term was attributed to gains from hybridization of drivetrains.

3.2 Technology drivers

In the second part, participants were asked to discuss the drivers (policy instruments, technology maturity, fuel production pathways, costs, required aftertreatment) affecting choice of future technology. The responses were grouped along different fuels, given below:

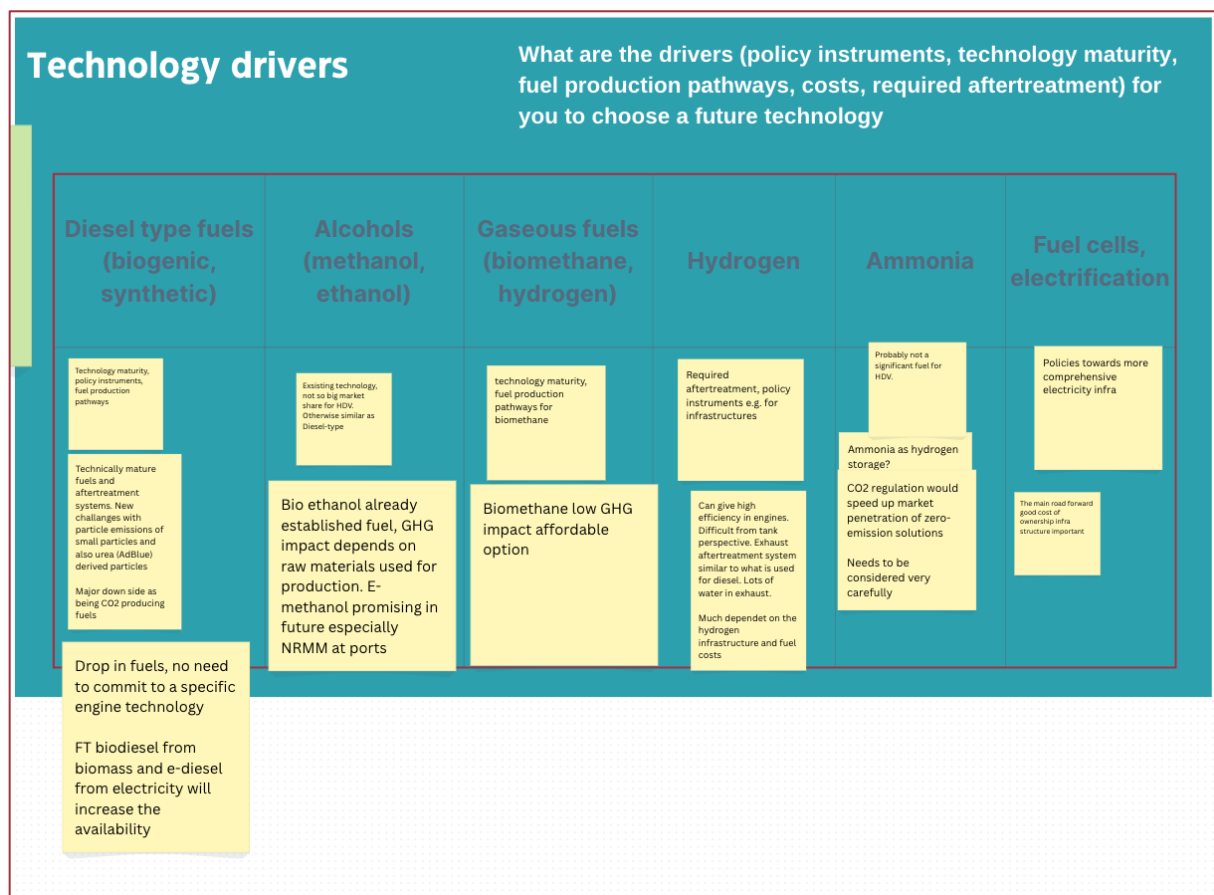


Figure 3-2: Board for discussing drivers of adoption

3.2.1 Diesel type fuels (biogenic, synthetic)

- Technology maturity, policy instruments, fuel production pathways
- Technically mature fuels and aftertreatment systems. New challenges with particle emissions of small particles and also urea (AdBlue)-derived particles
- Major down-side as being CO₂ producing fuels
- Drop-in fuels, no need to commit to a specific engine technology
- FT biodiesel from biomass and e-diesel from electricity will increase the availability

3.2.2 Alcohols (methanol, ethanol)

- Existing technology, not so big market share for HDV. Otherwise similar as Diesel-type

- Bio ethanol already established fuel, GHG impact depends on raw materials used for production
- E-methanol promising in future especially NRMM at ports

3.2.3 Gaseous fuels (biomethane, hydrogen)

- Technology maturity, fuel production pathways for biomethane
- Biomethane low GHG impact affordable option

3.2.4 Hydrogen

- Required aftertreatment, policy instruments e.g. for infrastructures
- Can give high efficiency in engines. Difficult from tank perspective
- Exhaust aftertreatment system similar to what is used for diesel
- Lots of water in exhaust
- Much dependent on the hydrogen infrastructure and fuel costs

3.2.5 Ammonia

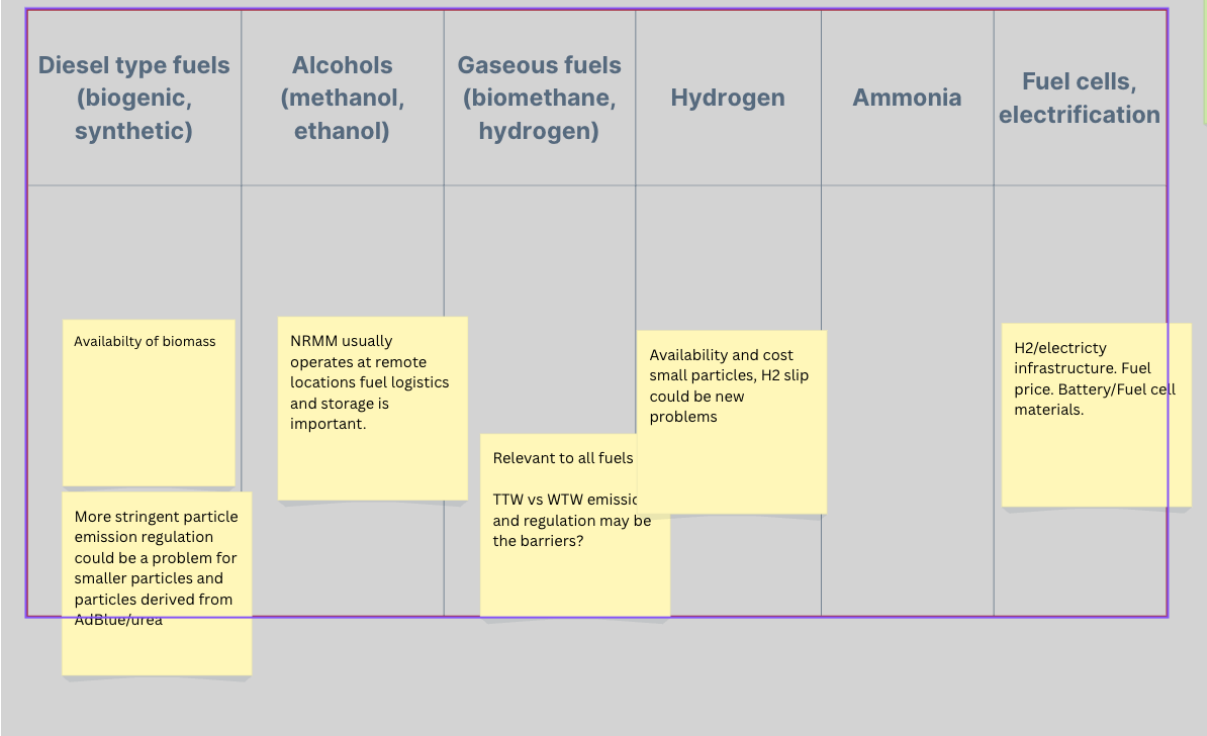
- Probably not a significant fuel for HDV
- Ammonia as hydrogen storage?
- CO₂ regulation would speed up market penetration of zero-emission solutions
- Needs to be considered very carefully

3.2.6 Fuel cells, electrification

- Policies towards more comprehensive electricity infrastructure
- The main road forward, good cost of ownership infrastructure important

3.3 Milestones and barriers

Major milestones and biggest barriers for the new fuels and technologies



In the last part, participants discussed the major milestones and potential barriers affecting uptake of different fuels and technologies.

Diesel type fuels (biogenic, synthetic)

- Availability of biomass
- More stringent particle emission regulation could be a problem for smaller particles and particles derived from AdBlue/urea

Alcohols (methanol, ethanol)

- NRMM usually operates at remote locations; fuel logistics and storage is important

Gaseous fuels (biomethane, hydrogen)

- Relevant to all fuels
- TTW vs WTW emissions and regulation may be the barriers?

Hydrogen

- Availability and cost
- Small particles, H₂ slip could be new problems

Fuel cells, electrification

- H₂/electricity infrastructure
- Fuel price
- Battery / fuel cell materials

3.4 Summary

- **Fuel mix expectations:** Stakeholders broadly agreed that drop-in diesel-type fuels will dominate HD and NRMM markets in the short term (to 2030), while electrification is expected to expand strongly by 2050, reaching roughly half of the market; ammonia was not considered a viable option even long term.
- **Sectoral differences:** Greater uncertainty was observed for non-road mobile machinery (NRMM), particularly regarding diesel-type fuels, while HD vehicles showed more convergent expectations across participants.
- **Efficiency gains:** Expected energy-efficiency improvements were modest in the near term (5–10%), mainly driven by drivetrain hybridisation, and higher in the longer term (10–25%).
- **Key technology drivers:** Adoption is shaped by policy instruments, technology maturity, fuel production pathways, infrastructure needs, costs, and aftertreatment requirements, with electrification supported by policy momentum and diesel-type fuels benefiting from maturity and drop-in compatibility.
- **Main barriers and milestones:** Critical barriers include biomass availability, particle emission regulation, fuel logistics for remote NRMM operation, hydrogen infrastructure and costs, TTW vs WTW emissions regulation, and material availability for batteries and fuel cells.

4 OUTCOMES OF THE AVIATION BREAK-OUT SESSION

Moderator: *Louise Ganeau,*

Rapporteur: *Jana Moldanova*

Participants: 6 external stakeholders with expertise in sustainable aviation fuels, airport sustainability management, sustainable flight operations, 3 REALCHEM partners

The session was introduced with a [presentation](#) on the technological trajectories for aviation and its impacts on air quality and climate. The participants were then invited to fill in their estimates of future development of absorption of alternative energy carriers, energy efficiency, and transport work having years 2030 and 2050 as reference points. Further discussions focused on the regulatory framework and technological developments in aviation and the participants were invited to document their opinion in form of post it notes in designated areas for Technology drivers, Major milestones, Biggest barriers and risk concerns for the new fuels and technologies. Finally, stakeholders' expectations, needs and recommendations for the Technology Packages of the REALCHEM projects were discussed.

4.1 Estimate of absorption of alternative energy carriers, energy efficiency and transport work in the sector in 2030 and 2050

In the first activity, participants indicated their expectations regarding the contribution of different fuels and technologies to the overall technology mix by placing a dot on the corresponding charts for the years 2030 and 2050. Participants were invited to pick their colour. In parallel, a second activity focused on the participants' views on future energy efficiency improvements and development of the traffic work volumes until 2030 and 2050. Based on these estimates, frequency distributions and mean values were calculated. The aggregated results of these activities are presented in Figures 4.1 and 4.2.

Technological Trajectories

(Mark your estimate with a dot)

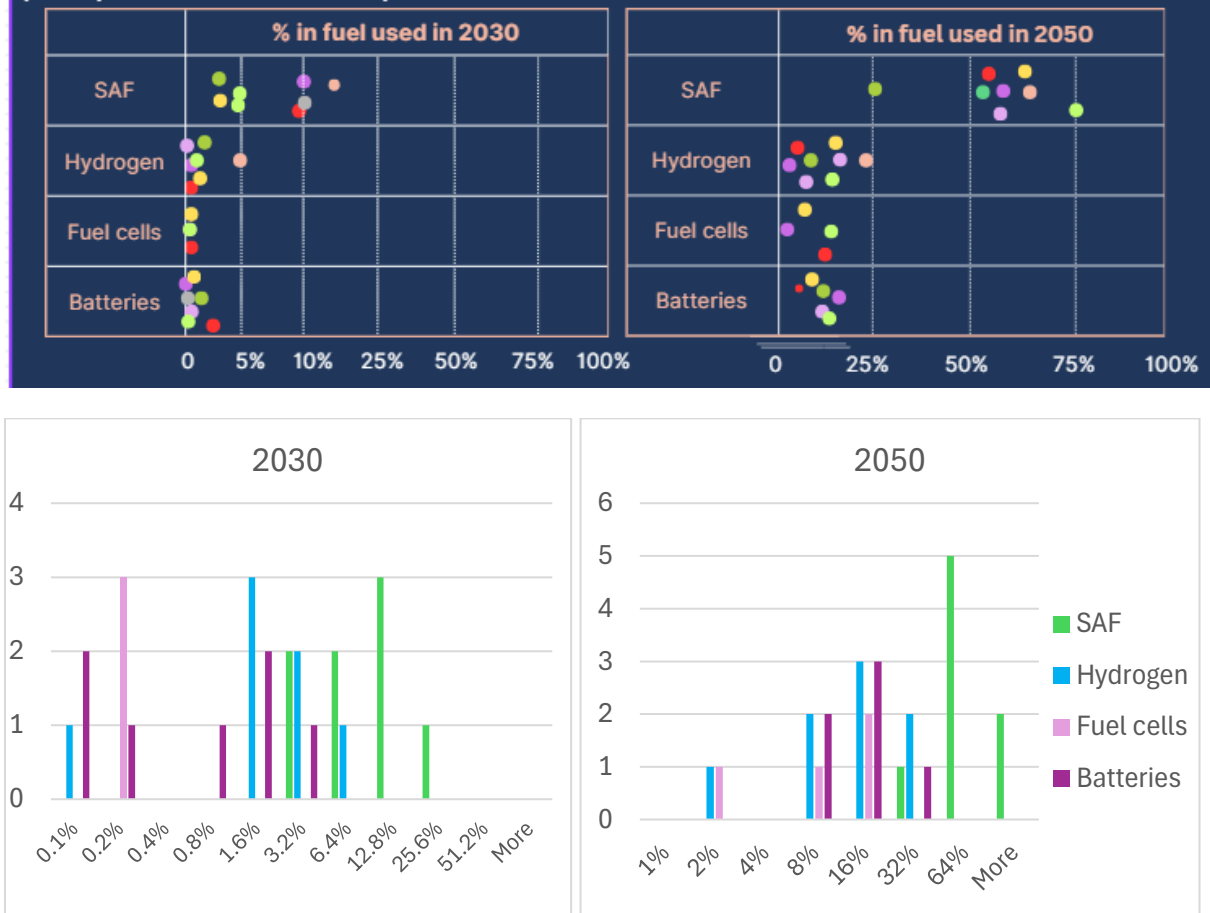
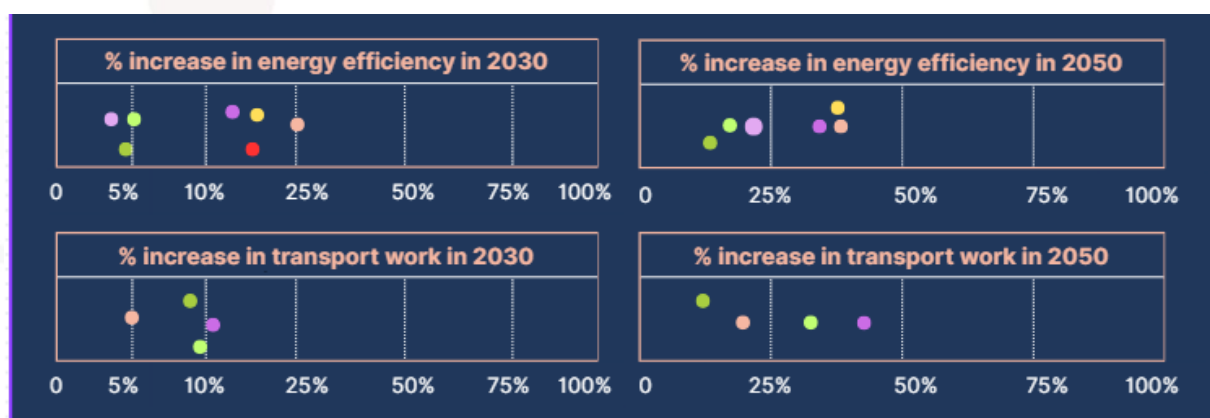


Figure 4.1. Participants' estimate of absorption of alternative energy carriers in the sector in years 2030 and 2050 indicated by dots in diagrams (upper part) and histograms of the estimates (lower part, mean values for 2030: 7.4% SAF, 1.9% hydrogen, 0.2% fuel cells, 0.8% batteries; 2050: 56% SAF, 12.5% hydrogen, 8% fuel cells, 11.2% batteries)



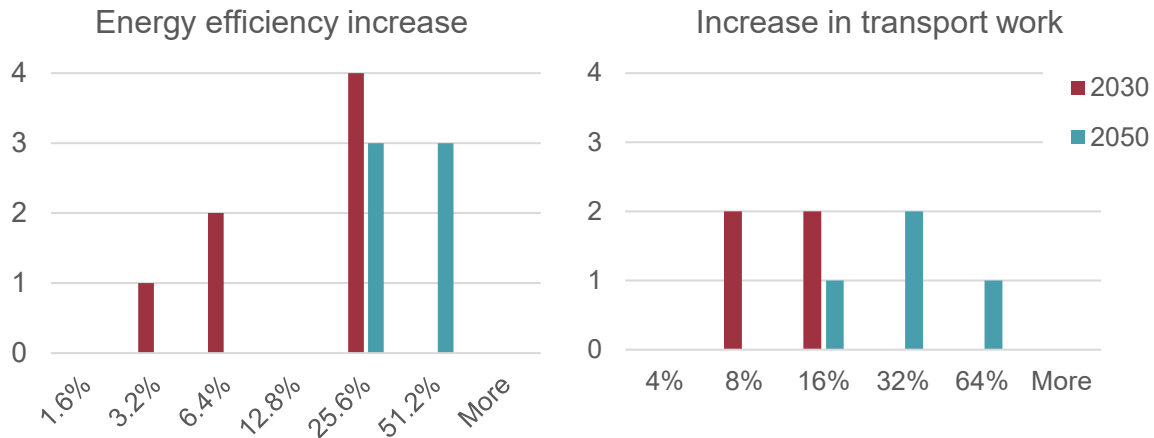


Figure 4.2. Participants' estimates of increase of energy efficiency and transport work in aviation from today to 2030 and 2050 indicated by dots in diagrams (upper part) and frequency distributions of the estimates for year 2030 and 2050 (lower part, mean value for the energy efficiency increase to 2030 12.7%, to 2050 26.3%, for the transport work increase to 2030 8.4%, to 2050 26.6%)

For 2030 the participants agreed that only small changes will take place in use of energy carriers as this is a short time horizon. The highest contribution to decarbonization is expected from use of drop-in SAF where 5-10 % of fuel use in aviation is expected, the mean value of the estimate is 7%. Technologies involving hydrogen as a fuel and new fuel cell and battery technologies are not yet mature compared to the use of SAFs. Participants believe that these technologies will be the least prevalent in 2030. For 2050 participants expect that contribution of SAF will increase approximately to 50 – 75%, the lowest individual estimate is an increase from 3% in 2030 to 25% in 2050. The mean of estimated use of SAF in 2050 is 56%. For 2050 use of other energy carriers, i.e. hydrogen, fuel cells and batteries is expected, however, still on rather low levels of approximately 10% for each carrier.

Development of energy efficiency to 2030 was estimated to improve by 5 – 25% (13% mean). Here the group was split between a lower estimate of ~5% and a higher estimate of 15 – 25%. At the same time, the development of the transport work was estimated to increase by 5 – 10% (8% mean). To 2050, the energy efficiency is expected to rise by 25 – 50% (26% mean) and the transport work by 10 – 40% (27% mean). this would mean that the major part in the energy efficiency increase would be eaten up by increased transport volumes. The transport volume estimates are based on input from just 4 participants.

4.2 Discussion on regulatory framework and technological developments

After discussing how different future technologies might evolve between now and 2030 and 2050, participants were asked to share their perspectives on the development of new regulations. Several aspects of regulation were discussed, including new fuel standards, stricter regulations on airport air quality and the decarbonisation of aviation from an environmental perspective. The various aspects raised by participants are presented below:

Decarbonisation and regulatory framework:

- Implementation of European decarbonisation policies, including ReFuelEU Aviation (European regulation to increase the use of sustainable aviation fuels as the single most powerful tool to decrease aviation CO₂ emissions), the EU ETS (European Union Emissions Trading System), and sustainability reporting frameworks.
- Regulatory developments related to the use of forest residues as feedstocks

Sustainability reporting and airport responsibility:

- Airports are responsible for decarbonisation of their own operations but must also account for emissions associated with their partners' activities (airlines, Scope 3 emissions).
- In 2050, CSRD (Corporate Sustainability Reporting Directive) is expected to cover both airport operations and partner activities, including airlines.
- Airport Carbon Accreditation (ACA) exists to reduce carbon emissions and the environmental impact of airports.
- A potential extension of the EU ETS could include the climate impact of aircraft contrails for aircraft operators.

Engine and fuel certification:

- Fuel composition, including the use of SAF up to 100% (neat SAF), is taken into consideration in engine emissions certification.
- Need to correct for different H content, aromatic content is an important parameter
- Decreasing aromatic content and sulphur content would decrease soot and particles but it would also be expensive and a need adaptation of the engine
- Certification specifications for hydrogen-powered aircraft are not ready yet

Air quality:

Regulatory framework for airports: EU Air quality directive

Airport monitoring stations: Ultrafine particles (UFP) are of concern due to the upcoming adoption of WHO's (World Health Organization) Guideline levels of Ultrafine particles.

Elemental/black carbon: 30% decrease of particle emissions from SAF blend.

Measurements of plumes performed at Kastrup, results not ready yet, 34% SAF blend, aromatic content not exactly known (~20%)

Workplace concentration levels important aspect for health impacts; airport/workplace levels of UFP, black carbon (BC)

4.3 Technology drivers

For each technological trajectories, participants then indicated what they considered to be the main drivers. SAFs received the most comments, as these trajectories built on the most proven technologies and are foreseen to be the most prevalent in future.

SAF:

- Reliable regulations
- Higher blends: Long term regulatory clarity that lowers the risk of investment
- SAF Mandates (Who must comply, Minimum mandatory share of SAF, Timeline, How – certification, reporting, penalties, e.g. EU ReFuelEU)
- Price guarantees, Contract for Difference (CfD), incentives
- Having value for fuel compositional quality on top of the sustainability

Hydrogen:

- Reduction of production cost (electricity cost & CAPEX), production increase to achieve economy of scale (all H₂-based fuels)
- Potential for almost zero emissions if NO_x emissions are solved

Fuel cells and batteries:

- Lower emissions at the airports when using batteries (airport maintenance staff and passengers); already in use but not the standard everywhere

4.4 Major milestones and biggest barriers and risk concerns for the new fuels and technologies

The development of future technologies may encounter barriers or risks related to their application, limiting their deployment. For each of the trajectories the participants have commented the major milestones and biggest barrier and the risk concerns.

SAF:

- Price, market, acceptance
- Flight companies are sensitive to fuel prices, for a long-haul flight ~30% of the cost is fuel. On the other hand, the cost is distributed among x*100 passengers – not a big cost per passenger.
- Supply, certificate, chain of custody, pricing of Jet-fuel is also part of airports competitiveness At CPH it is not possible to separate SAF from Jet-A in existing hydrant system
- New infrastructure needed to avoid cross-contamination for a *potential* 100% SAF system
- Strict fuel properties envelope
- Usage of different feedstock depending on region, for example GROT/forest residue in Sweden. The feedstock is a limited resource and has effects in other sectors (land use, food production etc.)
- Risk of emissions of emerging pollutants. E.g., content of FAME in bio-SAF may increase soot emissions

Hydrogen:

- High cost of Supply of “green hydrogen”
- Currently not energy efficient; energy density probably not feasible for the long-haul flights (for short / regional likely feasible)
- Infrastructure for safe distribution to and within airport
- Storage
- Safe aircraft fuelling
- Passenger acceptance
- NOx formation increases by using hydrogen (if abatement is not solved)

Fuel cells and batteries:

- Fuel cells require fuel: related to the introduction of hydrogen as aviation fuel
- Infrastructure readiness, high cost of infrastructure
- Energy density is probably not feasible for the long-haul
- Waste disposal and operation requirements at the airport

Open fan technology

- Integration into aircraft design concepts (safety, structure, noise)

4.5 Stakeholders' expectations, needs and recommendations for the Technology Packages

As the last

- Reliable engine emissions certification data from new sustainable fuel in addition to well-defined Jet-A reference.
- Fuel composition is critical for emissions and hence local air quality
- Improved and adapted engine Combustion technologies needed together with upcoming decarbonized fuels

4.6 Conclusions from the aviation session

- SAF is seen as the main decarbonisation option up to 2030, with limited uptake (~7%) in the short term but becoming dominant by 2050 (mean ~56%).
- Hydrogen, fuel cells and batteries are expected to play only a minor role, even by 2050, due to maturity, cost and infrastructure constraints. In the case of batteries and hydrogen, the low energy content is seen as a barrier preventing these energy carriers from being used for the long-haul flights.
- Energy-efficiency improvements are expected ($\approx 13\%$ by 2030; $\approx 26\%$ by 2050), but much of the gain risks being offset by growth in transport demand.
- Regulation is a key enabler, with ReFuelEU Aviation, EU ETS and sustainability reporting frameworks seen as decisive drivers.
- Mandates and price-support mechanisms (e.g. CfDs) are considered essential to reduce investment risk and enable higher SAF blends.
- Fuel composition matters, as aromatic and sulphur content strongly affect engine performance and local air quality.
- SAF faces barriers related to cost, supply chains, feedstock availability, certification and airport infrastructure compatibility.
- Hydrogen and electrification face high risks linked to cost, energy density, infrastructure, and safety.
- Stakeholders highlighted the need for robust emissions data, adapted engine technologies and clear certification frameworks to support future fuel and technology deployment.

5 FINAL REMARK

The results of this stakeholder meeting will be a vital input to the RealChem project. It will be used to choose and formulate a set of technology trajectories for each of the sectors (aviation, shipping, non-road and HDV). Further, the results will be used to as input to formulate scenarios used to model emissions and then for dispersion modelling. The information will also be used for formulating strategies and technology packages to mitigate emerging pollutants.