Strategic Energy Technology Plan

Implementation Working Group on
Renewable fuels and bioenergy

Thematic Vision on Renewable fuels and bioenergy

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Executive summary

Renewable fuels and bioenergy constitute a strategically indispensable pillar for achieving Europe's climate-neutrality objective by 2050 while strengthening energy security, resilience and strategic autonomy. The overarching priority of this Vision is to maximize the contribution of the renewable fuels and bioenergy to achieving net GHG emission by 2050, across all energy end-uses, in line with EU climate objectives.

In this transition, remaining demand for liquid and gaseous fuels shall be progressively and sustainably replaced by advanced biofuels and renewable fuels of non-biological origin (RFNBOs), while preserving openness to new and emerging solutions that may demonstrate superior system value over time. In the context of geopolitical instability, supply-chain disruptions and climate pressures, renewable fuels and bioenergy provide dispatchable energy and renewable carbon solutions that reduce fossil fuel imports, mobilise domestic resources and reinforce European industrial sovereignty.

This Vision integrates the full scope of renewable fuels and bioenergy under the SET Plan mandate while explicitly embedding energy security, advanced digitalisation and AI, circular carbon systems, concrete industrial deployment pathways, forestry and rural development, and robust regulatory governance. It follows a clear time-stepped trajectory for 2030, 2040 and 2050, ensuring that the overall system integrating resources and uses is optimized to deliver a bankable sustainable energy supply solution, while maintaining technological openness and innovation optionality.

1. Introduction

1.1. Scope and Purpose of the Thematic Vision

The purpose of the Vision is to articulate how this diverse technology portfolio can jointly contribute to Europe's climate-neutral energy system, while providing strategic guidance for research, innovation, demonstration, manufacturing scale-up and market uptake under the SET Plan.

This Vision covers the entire renewable fuels and bioenergy portfolio as defined in the SET Plan Mandate, including advanced liquid and gaseous biofuels, biomethane, solid biomass fuels, bioenergy for power generation and heating and cooling, biohydrogen from biological, biochemical and thermochemical pathways, renewable fuels of non-biological origin integrated with biogenic carbon, circular carbon systems, and emerging long-term options such as direct solar fuels[1]. This includes integrated production systems, renewable carbon management, industrial biocarbon and renewable carbon and nitrogen applications, including compliant with the overall system optimization substitution of fossil carbon in industry through sustainable biocarbon solutions and directly reduced carbon and nitrogen solutions.

The Vision provides strategic guidance for research, innovation, demonstration, manufacturing scale-up and market deployment in terms of renewable energy supply across all energy uses where renewable fuels and bioenergy can be utilized, while linking technology development to industrial competitiveness, territorial cohesion and long-term system resilience.

[1] Direct solar fuel technologies convert water, CO_2, and/or nitrogen into fuels (e.g. hydrocarbons and ammonia)

2. Vision and targets

2.1. Overarching Vision

Renewable fuels and bioenergy will form a comprehensive and technology-diverse pillar of Europe's climate-neutral, competitive and resilient energy system. Their deployment will be guided by sustainability, system integration and value optimisation, ensuring that the overall system integrating resources and uses is optimized to deliver a bankable sustainable energy supply solution, while maintaining innovation pathways for emerging and breakthrough technologies.

2.2. Quantified Renewable Fuel Volumes

This Vision is underpinned by a clear trajectory for renewable fuels and bioenergy across 2030, 2040 and 2050, reflecting system transformation, electrification and sectoral reallocation.

EU demand for transport is assessed to evolve as follows[2]

Year	Total RF demand excluding H2 (EU)	Biofuels demand (EU)	RFNBOs demand excluding H2 (EU)	H2 demand (EU)
2030	**~35–43 Mtoe**	**~32–40 Mtoe**	**~0,5-1 Mtoe**	**~1-2 Mtoe**
2040	**~65–68 Mtoe**	**~43–45 Mtoe**	**~22–23 Mtoe**	**~15–16 Mtoe**
2050	**~81–83 Mtoe**	**~45–46 Mtoe**	**~36–37 Mtoe**	**~39 Mtoe**

A few additional Mtoe would be needed for rail and inland navigation by 2050.

(2) European Commission: Directorate-General for Research and Innovation, Exergia, E3Modelling, Wageningen University & Research, BEST, BTG, POLITO, Georgiadou, M., Goumas, T. Chiaramonti, D. (eds), *Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels – Final report*, Publications Office of the European Union, 2024, **https://data.europa.eu/doi/10.2777/679307**

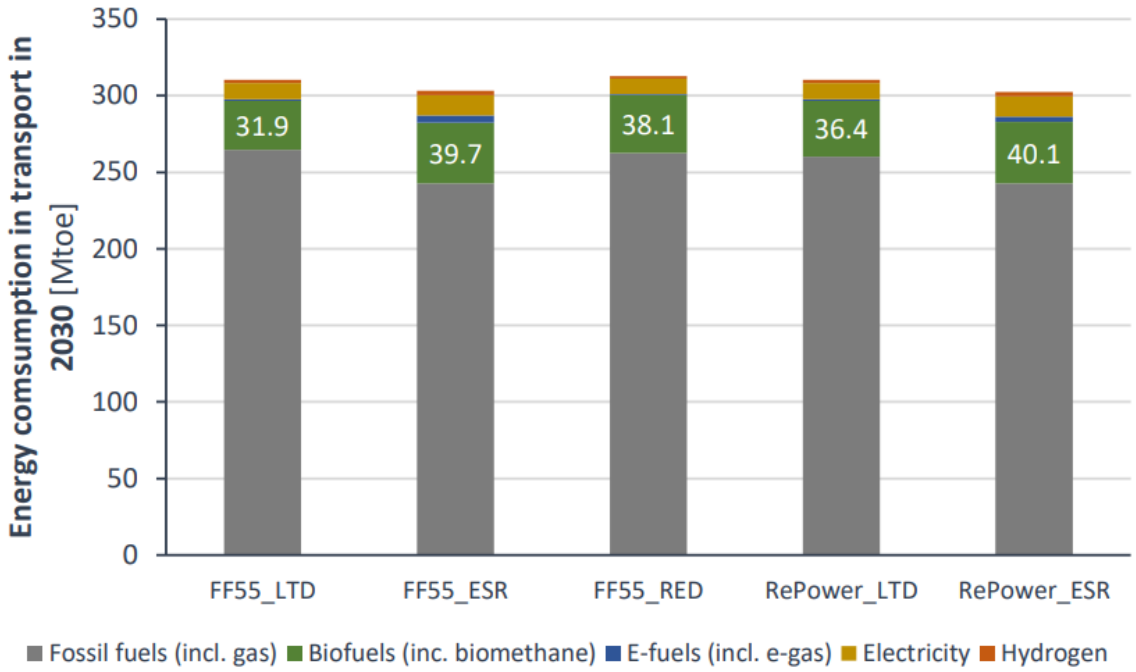

Figure 1 - Energy mix of the transportation sector in 2030 across the different variants

Source: PRIMES-TREMOVE transport model

- By 2030, demand is driven by continued use of combustion technologies, especially in transport and is mostly served by biofuels.
- By 2040, demand shifts to (advanced) biofuels and RFNBOs as renewable fuels are increasingly concentrated in aviation, maritime and other hard-to-abate sectors, with biofuels dominating by a factor of 2.
- By 2050, overall demand is in aviation and maritime due to electrification and efficiency gains and served by 60% advanced biofuels and 40% RFNBOs, while advanced biofuels and RFNBOs dominate remaining use.

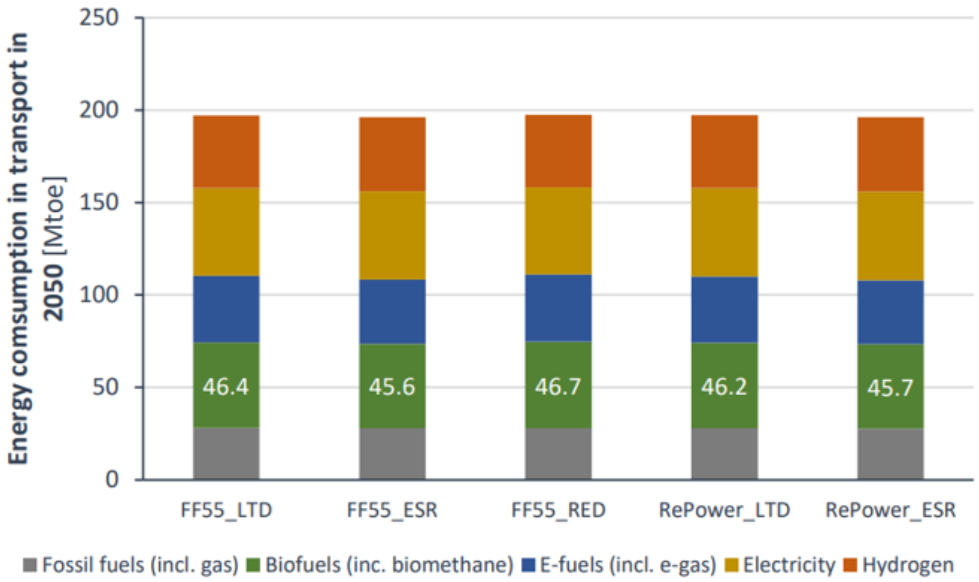

Figure 2 - Energy mix of the transportation sector in 2050 across the different variants

Source: PRIMES-TREMOVE transport model

Supply capacity develops in parallel[1]:

- ~27 Mtoe biofuels available by 2030 under current market condition, possible ~57 Mtoe → potential supply gap
- Broad alignment of supply and demand by 2040
- ~49 Mtoe biofuels available by 2050 under current market condition, possible ~130 Mtoe → mature and balanced system
- RFNBOs (excluding hydrogen) estimated capacity development in 2030[1] estimated from 0.01 to 2.69 Mtoe with the upper limit depending on realization of planned projects [3]
- Renewable H2 estimated capacity development in 2030[1] estimated from 0.023 to 6.891 Mtoe with the upper limit depending on realization of planned projects
- Estimations for RFNBOs capacity not very reliable for 2050 as many factors are involved (cost of electricity, cost of hydrogen, availability and cost of CO2, etc)

(3) including hydrogen converted to e-fuels for transport, i.e. e-kerosene, e-methanol, e-ammonia and e-methane

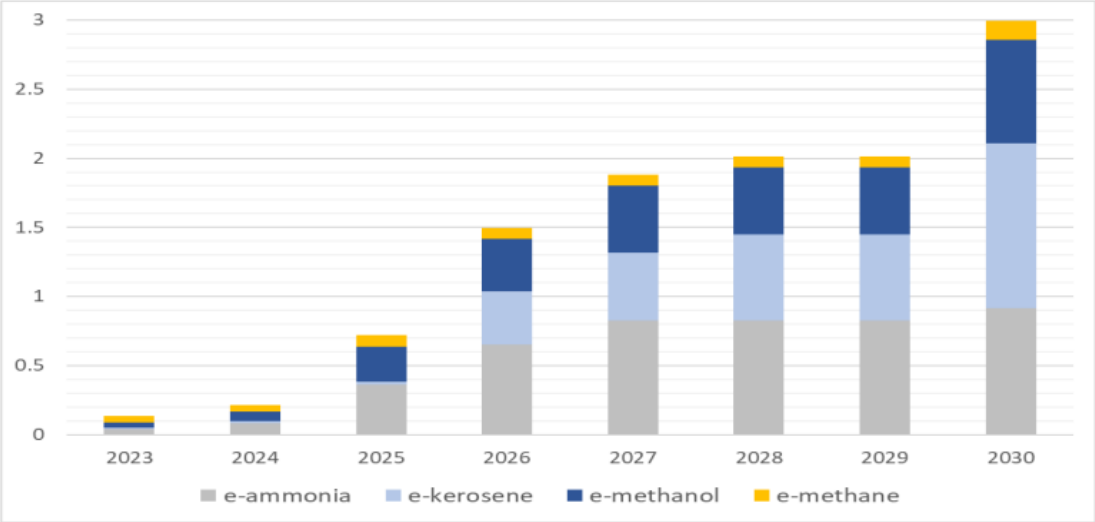

Figure 3 – Cumulated evolution of all assessed e-fuel production capacities (Mtoe/yr) excluding e-hydrogen, including capacities for industrial applications

Sectoral shifts:

- 2030: road transport dominates
- 2040: strong reallocation to aviation and maritime
- 2050: fuels used primarily in hard-to-electrify sectors

Overall, the system evolves from rapid scale-up (2030) to increasing demand and reallocation (2040) and finally to stabilized-volume use (2050) focused on highest-value applications.

2.3. Cross-Cutting Strategic Pillars

2.3.1. Energy Security, Resilience and Strategic Autonomy

Across all time horizons, renewable fuels and bioenergy shall contribute to:

- Reduction of fossil fuel imports and exposure to external shocks;
- Geopolitical resilience through diversified and domestic supply chains;
- Supply-chain security for feedstocks, technologies and infrastructure;
- Domestic feedstock mobilisation and stimulation, including residues and wastes from agriculture and forestry, biogenic CO, intermediate crops in combination with normal food production and crops from marginal and degraded lands.

Energy security considerations shall be systematically integrated into prioritisation, investment and policy design.

2.3.2. Advanced Digitalisation and Artificial Intelligence

Digital technologies are core enablers throughout the transition, including:

- End-to-end digital traceability of feedstocks, fuels and carbon flows;
- AI-enabled process and related functional systems optimisation;
- Predictive maintenance and reliability enhancement;
- Digital MRV systems for lifecycle GHG accounting;
- Lifecycle digital certification supporting harmonised EU markets.
- Digital optimisation of integrated sustainable energy vector supply solutions.

2.3.3. Circular Carbon Systems and Circular Carbon Hubs

The Vision adopts a Circular Carbon Hub approach integrating:

- CO_2 capture, utilisation and storage;
- Biogenic carbon mobilisation for biochar from biogas/biofuel production;
- Renewable hydrogen production from biomass or through direct conversion;
- Renewable ammonia production as an energy vector and fuel through direct conversion;
- Primary renewable fuel and side-product synthesis;
- Integrated energy driven biorefineries combining fuels, energy, materials and carbon management, including integration with renewable hydrogen and industrial CO_2 management systems as appropriate.

These hubs enable integrated CO_2/H_2/ammonia systems, industrial integration and net-negative emission pathways based on sustainable biogenic carbon or through direct CO2 or nitrogen reduction.

Particular attention should be given to maximising carbon efficiency, reducing residual waste streams and improving integration between biological and electrochemical conversion pathways.

2.4. Short-term goals (2030)

By 2030, Europe will:

- Scale-up commercially available renewable fuels and bioenergy solutions, including advanced biofuels, biomethane, solid biomass fuels and high-efficiency bioenergy systems;
- Reduce exposure to fossil imports through rapid deployment of domestic renewable fuel value chains;
- Advance technologies from pilot to commercial maturity and the deployment of first pre-commercial demonstrations, including First-Of-A-Kind (FOAK) industrial facilities for advanced biofuels and renewable fuel technologies, particularly for aviation, maritime and heavy-duty transport sectors;
- Integrate interoperable digital monitoring, MRV and traceability and robust carbon accounting systems for renewable fuels and bioenergy value chains;

- Improve sustainable biomass mobilisation, logistics and certification, including residues, wastes and low-quality resources, intermediate crops in combination with normal food production and crops from marginal and degraded lands;
- Enable the rapid deployment of biomethane production through addressing key infrastructure bottlenecks, including upgrading, injection and distributed plant deployment;
- Accelerate deployment of mature renewable fuel and bioenergy technologies while reducing innovation-to-market gaps for TRL 7–9 technologies;
- Improve carbon conversion efficiency and integration of technological modules in renewable fuel production systems;
- Scale-up alternative biogas production technologies such as pyro-gasification and hydrothermal gasification;
- Address regulatory and market barriers along the entire value chain, such as administrative compliance for feedstock under energy and agriculture EU policies, harmonised certification, sustainability accounting, carbon-credit rules and book and claim systems across EU MS,
- Provide financial support integrated under a single program for an integrated industrial value chain (feedstock, aggregation, conversion, logistics, infrastructure and offtake), biofuel and RFNBO production premiums or equivalent contracts for difference to close the price gap to fossil comparators.

Governance at this stage focuses on technology-neutral support, accelerated permitting and regulatory sandboxes to overcome regulatory gaps and hurdles.

2.5. Medium-term goals (2040)

By 2040, Europe will:

- Achieve large-scale market uptake of advanced biofuels and RFNBOs in aviation, maritime, heavy-duty transport and hard-to-abate industry, alongside continued electrification;
- Progressively displace fossil liquid fuels from residual transport and industrial applications;
- Deploy and consolidate circular carbon hubs at industrial scale, possibly by implementing energy driven integrated biorefineries combining fuels, power, heat, materials and carbon management; or other optimization models for addressing fluctuating transport and industrial energy process market demand at a cost-effective operational way;
- Prioritise renewable fuels and bioenergy for non-electrifiable applications and energy system balancing;
- Realise significant cost reductions driven by learning effects, digital optimisation and supply-chain maturity;
- Realise benefits such as contributing to wildfire prevention, hydrogeological protection and rural employment by strengthening multifunctional forestry and lignocellulosic biomass value chains;
- Realise sustainable biomass mobilisation and strategic land use by:
- Scaling rural development and fallow and abandoned land valorisation projects linked to renewable fuel value chains;
- Scaling intermediate crop valorisation projects linked to renewable fuel value chains in combination with normal food production;
- Apply stage-gated governance to progressively phase-out inefficient or non-scalable pathways;
- Scale circular carbon systems combining biogenic CO_2, renewable hydrogen and renewable fuel synthesis;
- Strengthen European manufacturing and industrial capabilities in strategic renewable fuel and bioenergy technologies;
- Develop modular and flexible production systems adaptable to evolving feedstock availability, market conditions and regulations;
- Strengthen regional biocircularity clusters supporting local value creation and resilient industrial ecosystems.
- Develop integration of CO2 capture, utilisation and storage, biogenic carbon mobilisation and renewable hydrogen production into Circular Carbon Hubs through initiating Circular Carbon Hub pilots in selected industrial and port regions;

2.6. Long-term goals (2050)

By 2050, Europe will:

- Achieve climate neutrality in the energy system
- Integrate renewable fuels and bioenergy as a complementary pillar alongside electricity and hydrogen by providing demand for liquid and gaseous fuels primarily through advanced biofuels and RFNBOs, deployed where electrification or direct hydrogen use is not feasible;
- Enable net-negative emission pathways through sustainable biomass use combined with carbon capture and storage;
- Maintain openness to emerging solutions, including direct solar fuels, which may contribute to the 2050 system, and produced on demand and in a decentralised way, compared to present centralised approaches;
- Operate within robust, harmonised sustainability and certification frameworks ensuring societal trust;
- Consolidate EU as a global leader in resilient and integrated renewable fuel, bioenergy and renewable carbon systems supporting strategic autonomy and territorial cohesion;
- Optimize sustainable valorisation of domestic biomass resources, residues and biogenic CO_2 while ensuring biodiversity protection and environmental integrity;

2.7. Priority R&I areas

2.7.1. Advanced renewable fuels for aviation, maritime and heavy-duty transport

Europe should accelerate the development and industrial deployment of advanced sustainable aviation fuels (SAF) and renewable maritime fuels, as well as advance biofuels for heavy duty transport beyond first-generation pathways. Priority R&I areas include:

- Gasification and Fischer-Tropsch conversion,
- Alcohol-to-Jet pathways,
- Renewable methanol and renewable marine fuels,
- Biomethane-based fuel synthesis,
- Direct solar fuels;
- Valorisation of biogenic CO_2,
- Hybrid biofuel / e-fuel systems,
- Process integration, feedstock flexibility and carbon efficiency improvements,
- Sustainability verification systems, and
- Industrial scale-up of TRL 7–9 technologies.

Reducing production costs and accelerating industrial deployment of first-of-a-kind commercial facilities in the EU should become a strategic priority.

2.7.2. Integrated biorefineries and circular carbon management

Future integrated biorefineries systems should optimize energy and resource efficiency, cost of production, circularity, and value creation. Priority R&I areas should include:

- Integrated production of fuels, energy and bioproducts,
- Biogenic CO_2 valorisation,
- Coupling with renewable hydrogen,
- Carbon capture and utilisation pathways,
- Nutrient recovery,
- Advanced outputs (digestate, others) management and valorisation, and
- Digital optimisation of integrated biocircular industrial systems.

The EU should prioritise technologies capable of maximising carbon efficiency while minimising residual waste streams.

2.7.3. Flexible and dispatchable renewable energy systems

Bioenergy and renewable fuels will play a critical role in providing flexibility, storage capacity and system resilience in increasingly electrified energy systems. Priority areas include:

- flexible biogas and biomethane systems,
- high-efficiency cogeneration,
- district heating integration,
- hybrid renewable systems.

2.7.4. Cross-cutting strategic considerations

Biogenic carbon as a strategic resource

Europe should increasingly consider sustainable biogenic carbon as a strategic resource for climate neutrality.

Biogenic carbon will be essential for renewable fuels, chemicals, co-products and long-term circular carbon management systems.

This requires improved biogenic CO_2 capture and management, integration of carbon management into industrial systems and harmonised renewable carbon traceability frameworks.

Integration between biofuels and electro-fuels

Renewable fuels comprise of biofuels and electro-fuels/ RFNBOs. Both will be necessary and complementary for achieving European climate neutrality objectives.

Strong synergies exist between biofuels and electro-fuels through use of biogenic CO_2, integrated biological and electrochemical conversion routes, and hybrid systems improving carbon efficiency and system performance.

The EU should therefore prioritise integrated renewable carbon ecosystems.

Territorial and industrial integration

Future European bioenergy systems should maximise territorial value creation and industrial integration.

Particular attention should be paid to regional biocircularity clusters, rural industrialisation, resilient domestic supply chains and optimisation of domestic organic resource use.

This systemic approach could become a major European competitive advantage in the transition towards a resilient and circular industrial economy.

2.8. Role of Renewable Fuels and Bioenergy in the Transport Transition

The transition of the EU transport sector towards climate-neutrality is an integral component of this Vision and is fully aligned with the overarching objective of achieving a decarbonised energy system by 2050.

At the same time, renewable fuels and bioenergy will play an increasingly strategic role in aviation, maritime, heavy-duty transport and hard-to-abate industrial sectors, where direct electrification remains technically or economically constrained and renewable molecules will remain indispensable over the long term.

The core objective for the transport sector is to reach net zero GHG emissions by 2050, through a balanced and system-realistic combination dominated by electrification and sustainable renewable fuels, while safeguarding energy security, industrial competitiveness and infrastructure feasibility.

2.8.1. Strategic orientation

Electrification as the backbone

- Electrification shall constitute the dominant decarbonisation pathway for road transport, particularly for passenger cars and light-duty vehicles.
- Deployment trajectories shall reflect grid capacity, charging infrastructure rollout and fleet turnover realities.

Renewable fuels for aviation, maritime and for residual and hard-to-electrify segments in road transport

Advanced biofuels and RFNBOs shall play a complementary and targeted role for:

- Aviation and shipping;
- Long-distance and heavy-duty road transport;
- Specialised and off-road applications;
- Legacy vehicle fleets during the transition period;
- Rail and inland navigation (at a lesser extend);
- Infrastructure- or geography-constrained contexts;
- Cross-border freight and logistics applications where infrastructure constraints remain significant.

These fuels contribute to system resilience, supply diversification and mitigation of transition risks.

Fossil fuel elimination

- By 2050, fossil fuels are severely reduced in all transport modes, with remaining liquid fuel demand supplied by sustainably certified advanced biofuels and RFNBOs.

2.8.2. Policy coherence and regulatory alignment

Transport decarbonisation pathways shall remain coherent with evolving EU legislation, including Regulation (EU) 2019/631, while preserving:

- Technology neutrality,
- Stage-gated governance linked to real-world performance,
- Openness to future innovations and emerging solutions that may complement electrification and renewable fuels,
- Industrial deployment, flagship projects and commercial-scale demonstration facilities.

2.9. Biomass, Forestry and Territorial Dimensions

Sustainably managed forest biomass and rural value chains are strategic enablers across all time horizons, supporting:

- Multifunctional forestry and forestry intercropping as a sustainable farming practice;
- Advanced lignocellulosic biomass conversion pathways;
- Intercropping with normal food production;
- Marginal and degraded lands cropping;
- Wildfire prevention, ecosystem resilience and hydrogeological protection;
- Rural economic development, employment and anti-depopulation strategies;
- Integrated valorisation of side-streams, residues and organic wastes through biocircular approaches;
- Development of regional biomass hubs and industrial symbiosis ecosystems.
- Territorial integration and domestic resource optimisation should become key elements of Europe's long-term resilience and strategic autonomy agenda.

2.10. Regulatory and Governance Framework

The transition requires a stable and enabling framework, including:

- Accelerated permitting and administrative simplification;
- Regulatory sandboxes for emerging technologies and business models;
- Harmonised lifecycle GHG accounting and certification systems;
- Harmonised sustainability beyond GHG accounting, carbon-credit rules and book and claim systems across EU;

- Compliance for feedstock under energy and agriculture EU policies
- Technology-neutral governance with temporal stage-gates guiding prioritisation over time and preserving openness to innovation.

2.11. Support for deployment

Strong support is needed for the large-scale deployment of technologies through, among others, public-private financing mechanisms, risk-sharing mechanisms, loan guarantees, tax credits, Contracts-for-Difference (CfDs) and long-term offtake agreements.

- Integration of support under a single program where feedstock, aggregation, conversion, logistics, infrastructure and offtake are financed together.

3. Conclusions and next steps

This time-stepped Thematic Vision clearly establishes the net zero GHG emissions by 2050 as its overriding objective to clean energy transition, while positioning advanced biofuels, RFNBOs and emerging renewable fuel solutions, including future direct solar fuels, as essential enablers of a resilient, competitive and climate-neutral European energy system, utilizing optimized integrated energy production systems and circular carbon systems. It provides a robust foundation for the SET Plan Strategic Research and Innovation Agenda and for coordinated European implementation and investment action.