



# ENOUGH

EUROPEAN FOOD CHAIN SUPPLY  
TO REDUCE GHG EMISSIONS BY 2050

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### Closing policy gaps for a low-carbon food chain in Europe

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## EXECUTIVE SUMMARY

The ENOUGH project aims to provide technical, economic, and political tools to make food-related emissions net-zero in the European Union (EU). For that aim, the WP2 developed technology roadmaps of the state-of-the-arts and future practices to reduce greenhouse gas (GHG) emissions across food supply chain (FSC) stages. This report identifies policy gaps in the European Commission's (EC) "FOOD 2030 Research and Innovation Pathways for action 2.0" report, which outlines research and innovation (R&I) priorities across eleven pathways to achieve sustainable, healthy, and inclusive food systems in Europe.

The identification of policy gaps across the EC's priorities is based on three ENOUGH technology roadmaps to decarbonize the (i) food transport, (ii) food cold storage, and (iii) domestic stages of the food supply chain. Every roadmap discusses a range of technologies that support decarbonization in their respective supply chain stages. Technologies are assessed according to availability and feasibility, as well as limiting factors to fully implement them. With a comprehensive understanding of needed technologies, we then analyse policy priorities envisioned by the Food 2030 report as a way to match what is needed from a technological standpoint to what is envisioned by a political proposal. In this way, we can assess policy gaps and opportunities to implement technological innovation in food industry operations. The Food 2030 report discusses future research and innovation priorities within 11 major pathways: (1) Governance for Food Systems Change; (2) Urban Food Systems Transformation; (3) Food from the Ocean and Freshwater Resources; (4) Alternative Proteins for Dietary Shift; (5) Food Waste and Resource-efficient Food Systems; (6) The Microbiome World; (7) Nutrition and Sustainable Healthy Diets; (8) Food Safety Systems of the Future; (9) Food Systems Africa; (10) Data & Digital Transformation; (11) Zero Pollution Food Systems. Following the ENOUGH project scope, not all pathways are applicable to the analysis. Therefore, the assessment was carried out for the following pathways: (1) Governance for food systems change; (2) Urban food systems transformation; (5) Food waste and resource-efficient food systems; and (11) Zero pollution food systems.

Each pathway outlines R&I investments and sets priorities to further research areas, making a link to climate sustainability co-benefits. They are, therefore, analysed according to the food industry and the technological limitations provided by the ENOUGH roadmaps. As a result, the present report provides gaps and suggestions that could be integrated to the current and future EC's priorities for R&I related to the food industry in the EU.

## Deliverable D7.7

### 1 INTRODUCTION

The food industry plays a critical role in shaping the European GHG emissions profile, with food systems estimated to contribute between 23% and 42% of global GHG emissions (Crippa et al., 2021). Within the EU, the yearly average per-capita GHG emissions from food supply is estimated around 1070 kg CO<sub>2</sub>-equivalent, varying significantly across countries (from 610 to 1460 kg CO<sub>2</sub>-eq.) largely driven by dietary patterns, particularly the consumption of animal products (Sandström et al., 2018). Moreover, when emissions embodied in trade and land-use change are accounted for, the climate impact of the EU's food consumption is substantially higher than the national production-based inventories suggest, revealing a major underestimation in conventional emissions accounting (Sandström et al., 2018). Addressing these emissions therefore requires a system-wide approach encompassing the design of roadmaps for all stages in the food value chain (e.g. production, processing, transportation, and consumption phases), as well as policy interventions to promote sustainable dietary transitions and reduce supply chain inefficiencies (Rabbi, 2025).

Among the stages of the FSC in the EU food industry, logistics and cold storage are pivotal yet often underappreciated contributors to GHG emissions across the FSC. Refrigerated transport and cold storage facilities are especially energy-intensive: life-cycle assessments indicate that the transport phase alone can account for over 80% of emissions within cold-chain logistics, particularly in the fruits and vegetables segment, with refrigerated transportation typically generating the largest share of GHG outputs (Li et al., 2025). Equipping trucks, ships, and trains with refrigeration units and maintaining temperature control during precooling, transit, and storage dramatically increases energy consumption compared to ambient-temperature logistics (Habibur Rahman et al., 2023).

Moreover, cold storage emissions stem not only from energy use but also from refrigerant leaks. For example, in the UK's food industry, refrigeration contributed approximately 12.9 Mt CO<sub>2</sub>-eq. in 2019 (about 3.5% of national emissions) with 50% tied to electricity for cooling and 56% of fugitive emissions originating from retail refrigeration systems; domestic fridges also represented a significant share (Foster et al., 2023). For these reasons, an analysis of the transport, storage, and domestic refrigeration sectors is timely. System-wide decarbonization strategies including optimized routing, low-GWP refrigerants, electrification, phase-change insulation materials, and improved energy efficiency are essential to reduce the heavy carbon burden of cold-chains in European food systems.

The ENOUGH project designed technological roadmaps as important tools for aligning innovation trajectories with long-term climate and sustainability goals, particularly within complex systems like the European food sector. These structured frameworks help identify priority technologies, estimate timelines for deployment, and assess barriers to adoption, thereby enabling policymakers to target interventions where they are most impactful. Roadmaps support policy making by identifying innovation pathways to allocate public and private investments to accelerate sustainable transition (Winebrake, 2004). In the context of

food system decarbonization, roadmaps can guide decisions on infrastructure modernization (e.g., energy-efficient cold storage), incentivize low-emission logistics, and support transitions toward circular resource use. Their structured, forward-looking nature allows governments to synchronize regulatory, financial, and industrial strategies with scientific advancements and market readiness, ensuring that innovation aligns with both environmental and economic objectives (Winebrake, 2004). Thus, technological roadmaps are not only planning tools but also instruments of governance that bridge the gap between climate commitments and actionable, sector-specific change.

These roadmaps are used to identify “policy gaps”, for which the scientific community and international organizations have raised some concerns in the areas of development strategies, climate change, and poverty alleviation. In relation to the political goal to decarbonize economies, a policy gap can be defined as the gap between a country’s commitment to reduce emissions and the actual policies enacted to achieve that target. It means that the proposed goals might not be achieved without policy enforcement in place. Policy gaps might also arise when countries are not ready to undergo proposed regulations due to financial means, market conditions, or lack of a well-defined structure to implement changes. Furthermore, policy gaps are also defined at the implementation level, when countries often sign up international macro-level commitments and do not count with local laws to implement them.

The EU has been the leading world region concerning environmental laws and policies. Since the launch of the European Green Deal (EGD) in 2019, the EC has been engaged in a gradual policy design and implementation scheme. This means that a fully harmonized policy package to decarbonize the EU economy is still neither completely proposed nor implemented. For instance, the Net-Zero Industry Act was proposed in March 2023 but entered into force in June 2024. Its implementation is a dynamic process that involves further delegated acts, national policy adjustments, and capacity building done according to EU members implementation capacity. Therefore, considering that several policies are still under elaboration, this report define policy gaps as *“themes, topics and issues that have not been taken into account by policy proposals, legal discussions, and policy priorities but are of core importance to effective zero-carbon operations according to ENOUGH’s decarbonization transport, cold storage, domestic roadmaps”*. Following from the political agreements and efforts to transform the European food sector, the D7.7 serves this process by supporting policy makers and multiple stakeholders involved in all FSC stages.

## 2 EU FOOD SECTOR EMISSIONS

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GHG emissions occur throughout the entire FSC, from production to consumption (Garnett, 2011). To effectively reduce emissions, policies should account for the unique characteristics of each stage, enabling targeted interventions that directly address emission sources.

In order to design appropriate interventions to reduce GHG emissions, it is necessary to understand the reduction potential for scope 1, 2, 3 emissions. These categories, defined by

the GHG Protocol<sup>1</sup>, provide a standardized framework for measuring GHG emissions. Breaking down emissions sources allows for comparing emissions across sectors and companies, and facilitates to target reduction areas and strategies.

Scope 1 emissions are also called “direct emissions” and stand for emission sources that are owned or directly emitted by a company. This means that the company has full control over such as combustion of fuels burnt in on-site operations and manufacturing processes.

Scope 2 emissions are those from purchased electricity, steam, heating, and cooling consumed by a company. Differently from scope 1, companies do not have full control of the emissions to produce energy, however, they are able to influence energy demand and opt for clean energy sources.

Scope 3 emissions are also called “indirect emissions” because they occur along the value chain (both upstream and downstream). These are emissions from the production of products and services bought by a company (upstream), waste disposal (downstream), among others. They are often difficult to measure.

The ENOUGH project estimates scope 1, 2 and 3 emissions inventories across FSC stages for ten European countries (Norway, Germany, United Kingdom, Italy, France, Belgium, Lithuania, Austria, Poland, and Hungary) for the base year 2019. The data offers granularity to assess emissions for each scope across all FSC stages: Agriculture, fishing and aquaculture, Food Manufacture, Storage and logistics, Freight transport, Retail and wholesale trade, Food and beverage service, and Domestic food consumption. The data differs from the EDGAR<sup>2</sup> model by providing sector-specific detailed information of emissions by scope. This allows for sector comparison and more importantly, targeting high-emission sectors according to the type of emissions, so to design interventions to reduce emissions.

While agriculture is an important GHG emitter and is at the forefront of the F2F strategy for policy interventions, downstream stages also play a crucial role. According to the ENOUGH inventory data, scope 1 emissions account for 54% of the food-related emissions, followed by scope 2 (29%), and scope 3 (17%). Agriculture is the major contributor to direct emissions, being responsible for 33% of total scope 1 emissions (60 MtCO<sub>2e</sub>). However, downstream sectors are the primary source of on-site emissions within the food sector. The GHG inventories show that food manufacture is a key GHG emitter both in scope 1 and scope 2 emissions, followed by food retail and domestic food consumption. Scope 3 emissions are represented in the ENOUGH inventory through packaging, as well as solid and liquid waste.

Political efforts to reduce GHG in agriculture are extensive and often supported by a range of incentives targeting stakeholders and specific agricultural activities. Many initiatives targeting the food sector tend to focus on agricultural practices. For instance, a key element to support the F2F strategy is an ambitious roadmap<sup>3</sup> developed by the EC, which aims to combine a series of policy and economic incentives to build an “attractive, competitive,

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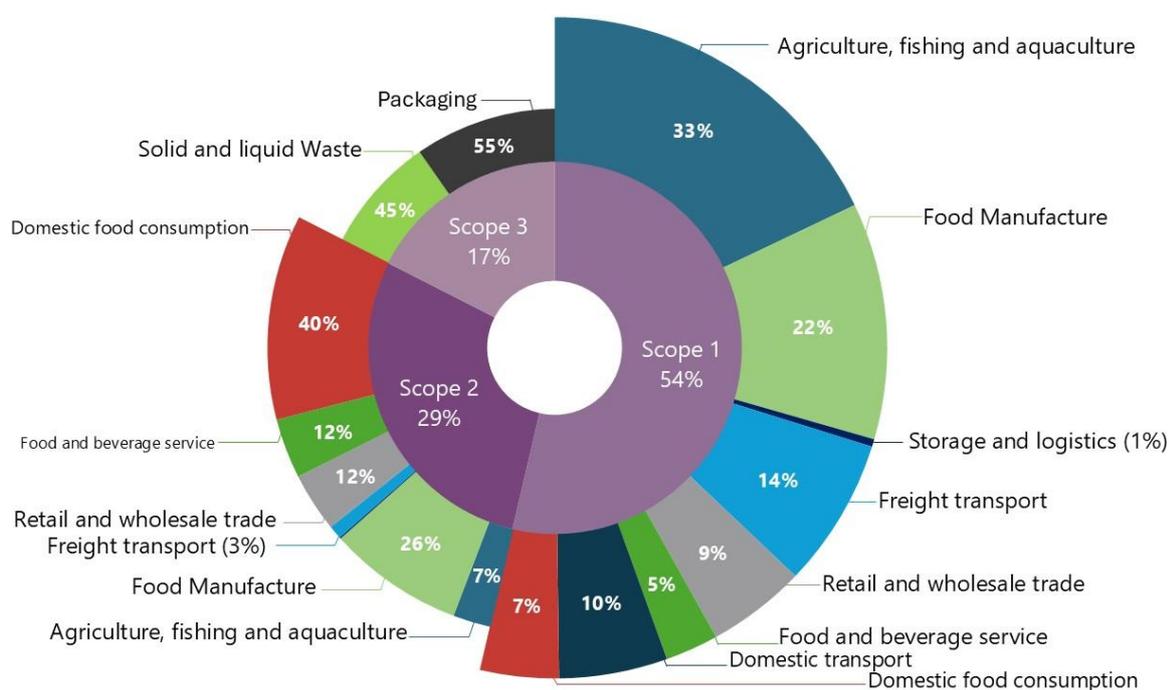
<sup>1</sup> Homepage GHG protocol: <https://ghgprotocol.org>

<sup>2</sup> Estimation data from EDGAR: <https://edgar.jrc.ec.europa.eu/>.

<sup>3</sup> [Commission presents its roadmap for a thriving EU farming and agri-food sector](#)

resilient, future-oriented and fair agri-food system for current and future generations of farmers and agri-food operators”. However, this vision focuses mostly on the agricultural sector, overlooking downstream sectors and their respective importance to reach net-zero targets by 2030. The entire food supply chain is deeply interconnected, involving companies and markets across multiple stages. Activities such as food manufacturing, transport, retail, and wholesale services together have a significant environmental impact and therefore warrant equal political attention. This underscores the need for coordinated and integrated policy efforts to ensure that all stages of the EU food supply chain are comprehensively addressed.

*Figure 1. Breakdown of Scope 1,2, and 3 GHG emissions by sectors of the food supply chain in ten European countries (Norway, Germany, United Kingdom, Italy, France, Belgium, Lithuania, Austria, Poland, Hungary) for the base year 2019.*



### 3 METHODS

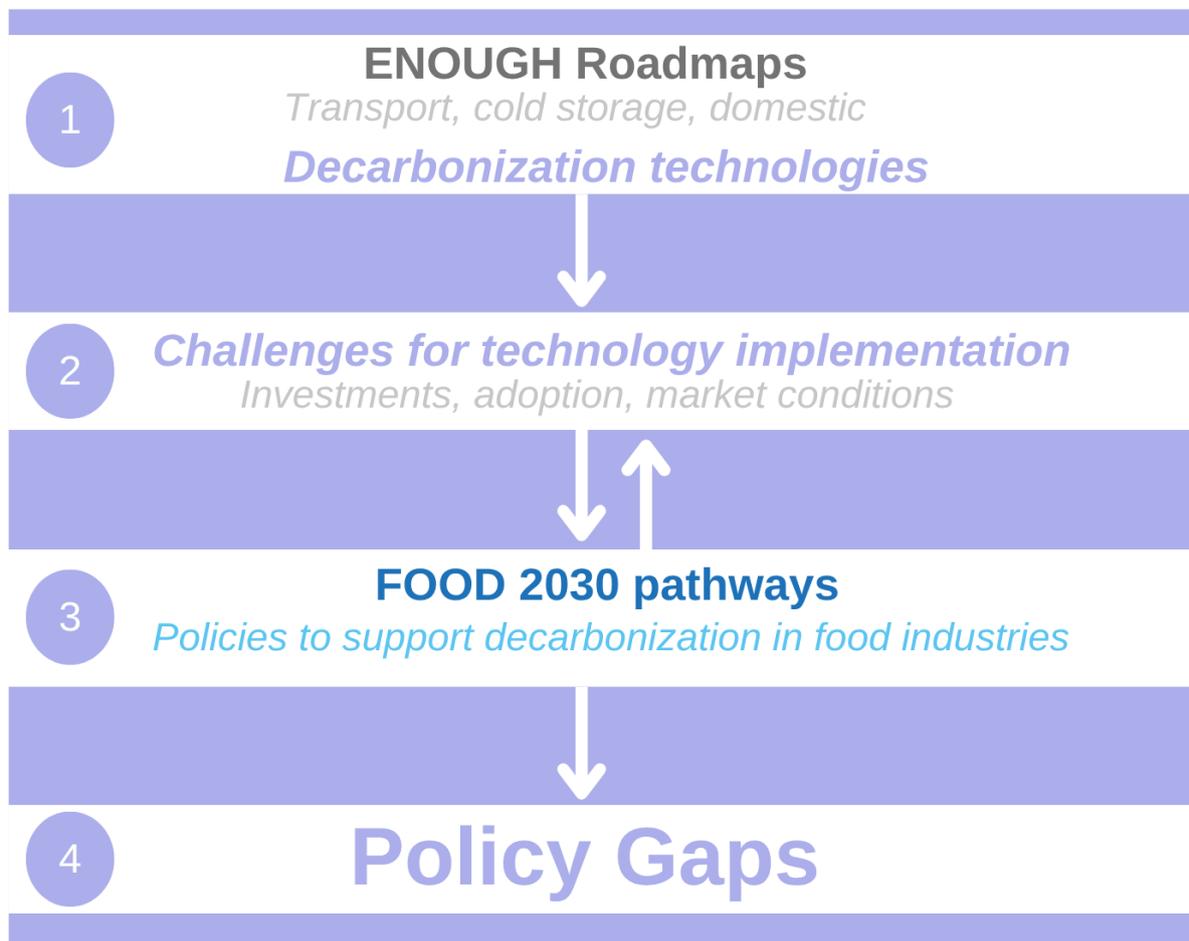
The methodological approach (Figure 2) involves aligning the technological roadmaps developed by the ENOUGH project with the “FOOD 2030 Research and Innovation – Pathways for action 2.0”<sup>4</sup> framework. The goal is to identify policy gaps related to technological development in downstream food sectors in the EU.

The process comprises four main steps:

<sup>4</sup> [New Report: Food 2030 Research and Innovation – Pathways for action 2.0 - European Commission](#)

- (i) using the ENOUGH roadmaps to establish a technological baseline that identifies the type of interventions needed to reduce GHG in cold storage, transport, and domestic consumption sectors.
- (ii) outlining the key challenges that hinder adoption and implementation of those technologies.
- (iii) assessing the EC’s “FOOD 2030” pathways and policy priorities related to the ENOUGH scope, aiming to promote decarbonization in food industries.
- (iv) identifying missing elements required to drive technological innovation and enable a full transition to cleaner and more efficient technologies.

Figure 2. Methodological approach to match ENOUGH technology roadmaps and the European Commission’s FOOD 2030 pathways with the aim to spot policy gaps.



## 4 ROADMAPS & TECHNOLOGY

In this section the three roadmaps and respective technologies are discussed by identifying their characteristics, market availability and limitations to their adoption based on the information and analyses provided by the ENOUGH roadmaps.

## 4.1 Food transport roadmap

Food transport is a major contributor to post-farm gate emissions, representing approximately 20% of the food system’s total GHG footprint. Road transport is the dominant mode to transport food in the EU, accounting for 77% of food freight, and thus represents a critical point for targeted interventions. Food transport emissions stem from diesel use, refrigerant leaks, and electricity consumption (Scope 1 and 2). Refrigerated transport is particularly emission-intensive, due to fuel for refrigeration units (TRUs) and high refrigerant leakage rates (10–37% annually). Despite representing a smaller share of tonne-kilometres, temperature-controlled freight has significantly higher GHG intensity (up to 0.66 kg CO<sub>2</sub>eq/tonne-km) than ambient freight.

The food transport roadmap reviews 29 technologies grouped across four categories: (i) Fuels & Power Sources; (ii) Insulation & Body Design; (iii) Refrigeration Technologies; and (iv) Digital & Logistic Technologies.

*Table 1. Food transport roadmap technologies description, market availability and limitations across four main categories: fuels and power sources, insulation and body design, refrigeration technologies, and digital and logistic technologies.*

Technology category	Technology	Description	Market availability	Limitation
<b>Fuel &amp; Energy Sources</b>	Biomethane	Provides reductions in direct carbon emissions and is compatible with existing combustion engines	Its availability varies by region	Infrastructure for widespread adoption is currently limited
	Hydrogen	Fuel cells are a clean energy solution with growing interest, particularly for medium- and long-distance transport. While hydrogen vehicles produce zero tailpipe emissions, the technology is still emerging	Not fully ready to the market	Fuel storage challenges, limited refuelling infrastructure, and high costs
	Photovoltaic panels	Can be installed on vehicles to partially power refrigeration or auxiliaries	Increasingly available and help offset electricity usage	Energy contribution is weather-dependent and generally insufficient to power large refrigeration systems alone.

	Electrification	Supports significant emission reductions when paired with a clean electricity grid	Commercially viable and expanding rapidly	Medium and heavy vehicle electrification is in earlier stages and limited by battery range, payload penalties, and charging infrastructure
<b>Insulation and Body Design Technologies</b>	Door curtains and seals	Simple, cost-effective measures that reduce air infiltration during loading/unloading	Widely available and show significant impact in reducing thermal losses	Correct maintenance and fit.
	Improved insulation materials	Upgraded polyurethane foams or aerogels, offer better thermal resistance. These materials can be integrated into vehicle walls to reduce heat ingress	While standard foam insulation is widely used, high-performance materials like aerogels or vacuum-insulated panels (VIPs) are less available	High cost and manufacturing constraints.
	Controlled atmosphere (CA)	Systems manage oxygen and carbon dioxide levels inside the refrigerated space to prolong freshness.	Commercially available and effective for certain food types (e.g., produce)	Require close monitoring and maintenance.
	Eutectic plates and thermal energy storage (TES)	Systems store cold energy, allowing refrigeration to continue during delivery without active cooling.	Commercially available and reduce emissions during off-engine operation	They require pre-charging (usually overnight), and their capacity limits trip duration.
	Surface coatings and reflective external finishes	Aim to reduce solar heat gain but are mostly in R&D	Limited commercial application	Their potential is promising, but standardisation and durability in harsh transport environments are concerns.
<b>Refrigeration Technologies</b>	Natural refrigerants like carbon dioxide (R744) and	Offer strong performance and very low global warming potential	These refrigerants are entering the market	Regulations (flammability for R290, high pressure for R744), installer

	hydrocarbons (R290)	(GWP). R290 slightly outperforms R744 in most locations		expertise, and availability of compatible equipment
	Cryogenic systems	Emit very low noise and can achieve a rapid temperature pull-down of the refrigerated space	Commercially available and attractive for short, intensive cooling needs	Require regular refilling and present safety/environmental concerns regarding venting gases
	Compressor control technologies	Optimize energy use by modulating compressor output	Are already available and offer meaningful energy savings	Benefits depend on the operating profile and compatibility with existing refrigeration units
	Air cycle and absorption systems	Lower the overall energy input for a given expansion pressure ratio	Under development but not yet widely adopted	Their efficiency is lower than vapor-compression systems, and size or complexity limits their commercial readiness
<b>Digital and Logistics Strategies</b>	Artificial intelligence (AI) and machine learning technologies	Optimize routing, predict maintenance needs, and improve loading schedules	High, especially through third-party logistics software	Training these systems requires energy, and implementation demands skilled personnel and digital infrastructure
	Internet of Things (IoT)	Provide real-time monitoring and improve decision-making	Applications such as wireless sensors, GPS, and temperature tracking are maturing rapidly	The challenge lies in network reliability, sensor calibration, and battery life
	Blockchain and decentralised ledger technologies (DLTs)	Emerging tools for secure and transparent supply chain data	Integration into logistics networks is still limited	While promising, they are energy-intensive
	Vehicle routing optimization	Uses mathematical programming to reduce distance travelled, improve load factor, and reduce delivery	Mature and widely available	Requires companies to align their operations with digital decision tools

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Source: ENOUGH's food transport roadmap (D2.5): [Publications - Enough](#).

## Assessment for the transport roadmap

Most technologies in the refrigerated transport sector are constrained by the level of investment required for their implementation and the significant infrastructural changes necessary across vehicle fleets, refrigeration units, and associated logistics systems. Deploying energy-efficient transport practices, tracking their performance over time, and fostering widespread industry adoption requires a well-defined action plan that integrates technical, financial, and political dimensions. Among the primary barriers to adoption, funding remains a significant challenge, particularly for small and medium-sized enterprises (SMEs), which often lack the capital or access to finance to invest in low-emission transport technologies or retrofitting existing fleets with energy-efficient systems.

In addition to financial constraints, there is a clear need for consistent enforcement of energy and emissions regulations within the transport sector. This includes not only setting clear performance standards for vehicles and refrigeration units but also ensuring compliance through regular inspections and monitoring of fuel use, refrigerant leakage, and energy consumption.

From a political perspective, there is a strong case for developing coherent and coordinated policy frameworks that prioritize energy efficiency and carbon reduction in food transport logistics. Increasing the availability and accessibility of funding, particularly for SMEs, through targeted loans or grant schemes would help accelerate technology uptake. Moreover, strengthening regulatory enforcement and establishing minimum energy performance standards for transport refrigeration units would ensure a level playing field across the industry. Incentivizing the adoption of energy-efficient transport technologies (e.g. electric and hydrogen-powered vehicles, low-GWP refrigeration systems, and advanced insulation) through fiscal measures like tax credits or subsidies would further support the transition. Finally, there is a need to invest in workforce development by creating training programs for drivers, fleet managers, and technicians to promote best practices in low-carbon transport operations. Support for innovation and research into advanced transport refrigeration technologies will also be critical to driving long-term improvements in efficiency and emissions reductions across the sector.

### 4.2 Food cold storage roadmap

Food cold storage plays a crucial role in the global food supply chain, particularly in the transportation and storage of perishable goods. The sector is responsible for 1% of global GHG emissions (Ravishanka et al., 2020) and presents several opportunities to reduce emissions in areas like energy consumption required to maintain refrigerated temperatures, transportation, and refrigeration facilities.

**Energy consumption:** Food cold storage facilities require significant amounts of energy to maintain refrigerated temperatures, which is typically generated by fossil fuels, leading to GHG emissions.

**Transportation emissions:** The transportation of perishable goods to and from cold storage facilities also contributes to GHG emissions.

**Cold chain inefficiencies:** Inefficiencies in the cold chain, such as temperature fluctuations and equipment malfunctions, can lead to increased energy consumption and GHG emissions.

The food cold storage roadmap identifies 30 technologies and strategies that can be applied to reduce carbon emissions in different settings of cold stores and mostly support the phasing out of GHG scope 2 emissions.

*Table 2. Food cold storage roadmap technologies description, market availability and limitations*

Technology	Description	Market availability	Limitation
Automation	Offers various routes to more energy-efficient operation of cold storage facilities	Widely available. Used in advanced facilities for energy optimization and labour efficiency	Limited adoption due to high costs
Compressors & controls	Variable speed/capacity control can offer energy savings of 15 to 40%	Commercially available. Includes high-efficiency compressors and smart control systems	
Condenser control	Floating head pressure can save 5 to 12% of system energy consumption	Available. Widely applied with variable speed drives and fan control strategies	
Defrosts & defrost controls	Hot gas defrosts are more thermodynamically efficient than electric heaters	Available. Includes advanced methods like demand defrost and smart control systems	
Demand side response (DSR)	Can relieve the strain on power grids by balancing energy consumption and production	Limited availability. Potential exists but uptake is low; pilot programs under way	
Doors & door protection	Infiltration of warm, moist air through open doorways is a major heat load on cold stores	Available. Includes insulated and automatic doors; widely deployed for energy efficiency	
Free cooling	Can introduce ambient air during periods when it is colder outside the chilled store	Site-specific availability. Available in suitable climates; not universally applicable	
Heat reclaim/recovery	Can be used to recover heat from refrigeration systems and	Available. Proven technology but adoption	

	use it for heating purposes	varies based on system design	
High temperature CA storage	Allow room temperatures to be raised and energy consumption from cooling machines to be reduced	Emerging. Not widely commercialized; requires further development for broader uptake	
Humidification	Reduce post-harvest losses of high moisture content perishable products	Available. Common in facilities storing fresh produce; integrated into control systems	
Insulation	Reduce transmission of heat through cold storage insulation, leading to energy savings	Mature market. High-performance insulation materials are widely available	
Internal loading & unloading bays	Reduce the risk of ingress of warm ambient air around imperfect loading bay seals	Standard practice. Includes air curtains, vestibules, and fast-closing doors	
Maintenance	Correct operating temperatures and prevent gradual degradation of energy efficiency	Essential and available. Services and contracts for energy-efficient operation are standard	
Monitoring	Enable changes in the performance of a store to be highlighted and early intervention can be implemented to repair or identify the reason for changes in performance	Widely available. Includes IoT, sensors, BMS systems for energy and temperature tracking	
Postharvest treatments	Reduce respiration and extend shelf life of fruits and vegetables	Available. Technologies vary by commodity; commercial solutions exist	
Renewable energy (solar electricity)	Generate electricity and reduce the reliance on natural gas	Available. Photovoltaic (PV) systems are increasingly integrated in cold storage facilities	
Renewable energy (solar thermal)	Provide heat and reduce the need for natural gas	Less common. Available but less frequently used than solar PV in cold storage settings	
Waste technologies &	Anaerobic digestion and	Emerging interest.	

impact of changes	composting are two of the best alternatives to food waste management in terms of GHG emissions	Technologies like anaerobic digestion and heat recovery from waste streams are underutilized	
CO2 scrubbers	Reduce the energy required to maintain the atmosphere in cold stores, leading to energy savings and reduced emissions	Limited availability. Primarily used in specialized Controlled Atmosphere (CA) or Dynamic CA systems; niche applications	Not applicable to all types of cold storage
Dynamic control atmosphere storage systems	Reduce energy consumption by 5 to 14%	Available but not widely deployed. Technologically mature but requires specific commodity conditions and higher capital cost	
Electronic Expansion Valves	Offer greater potential to optimize refrigeration system performance and enhance efficiency	Commercially available. Widely used in modern systems for precise refrigerant control	
Energy storage (thermal and electrical)	Shift the electrical energy consumption of refrigeration plants, allowing peak shaving and shifting of refrigeration plant operation to more efficient ambient periods	Emerging. Growing interest, especially thermal storage	
Evaporative and adiabatic condensers	Offer energy savings of up to 58% compared to dry condensers	Commercially available. Especially in warm climates; well-established technology	
Evaporator fans & speed controls	Deliver energy savings of around 40% compared to fixed-speed AC fans	Widely available. Variable-speed fan drives are standard in efficient systems	
Lighting and light controls	Use less than half of the energy for similar levels of lighting compared with more traditional types of lights	Mature technology. LED lighting and smart controls are widely used in modern facilities	
Natural refrigerants	Used in larger low-temperature refrigeration systems	Increasing availability. CO <sub>2</sub> , ammonia, and hydrocarbons are gaining market share	

Stacking patterns	Determine the airflow rate through the pallet	Operational measure, not a product. Techniques are available and implemented; effectiveness varies by commodity and layout	
Temperature control set points	Setting the temperatures which cold store refrigeration systems are trying to maintain is important to consider at what temperature the desired retention of food quality and safety will be achieved	Standard practice. Available through most refrigeration control systems; optimization is application-specific	

Source: ENOUGH’s food cold storage roadmap (D2.4): [Publications - Enough](#)

### Assessment for cold storage roadmap technologies

Most technologies are limited by the investments needed to support their implementation and to enable significant infrastructural changes in cold stores. In fact, implementing energy-efficient practices, monitor and evaluate the progress of the interventions, and encouraging industry-wide adoption of technologies requires a solid action plan encompassing technical, financial, and political interventions. Funding is the main constraint to the adoption of energy efficient technologies especially by SMEs in the cold storage sector, a fact that make it difficult for them to invest in energy-efficient technologies and practices. Additionally, there is a need for effective enforcement of energy efficiency regulations including regular inspections and monitoring of energy consumption.

From a political standpoint, policies recommendations are: (i) the development and implementation of consistent political guidelines and action plan to promote energy efficiency and emissions reduction requirements in cold storage facilities; (ii) increase funding for energy efficiency measures; (iii) improve funding access to SMEs including loans and grants; (iv) improve enforcement of energy efficiency regulations including regular inspections and monitoring of energy consumption; (v) Developing and implementing energy efficiency standards for cold storage facilities, including minimum energy efficiency requirements for refrigeration systems and insulation; (vi) Providing incentives for energy-efficient technologies, such as tax credits or grants, to encourage cold storage operators to invest in energy-efficient equipment and practices; (vii) Developing and implementing training programs for cold storage operators and maintenance personnel on energy efficiency and emissions reduction, as well as the benefits of energy-efficient technologies and practices; (viii) Supporting research and development in the cold storage sector.

### 4.3 Domestic Roadmap

Domestic kitchens significantly contribute to post-farm gate GHG emissions, which represent about 20% of the global food chain’s emissions. Most domestic emissions come from cooking and refrigeration, key daily activities in food handling. Cooking uses approximately 6% and refrigeration 5% of household energy consumption. There are considerable opportunities to reduce GHG emissions in the food domestic sector especially in areas to improve energy efficiency of appliances and outdated cooking methods.

The ENOUGH’s domestic roadmap outlines 54 technologies divided in refrigeration, cooking, and ancillaries, of which only those available on the market and those that are operational were evaluated. Thus, a total of 12 technologies were selected and analysed (Table 3).

*Table 3. Domestic roadmap technologies description, market availability and limitations across three technology categories: refrigeration, cooking, and ancillary technologies.*

Technology category	Technology	Description	Market Availability	Limitations
Refrigeration technologies	Improved insulation (e.g., vacuum insulated panels)	Substantially reduces thermal losses and can lower energy consumption from 20 to 40%	Still limited to high-end or experimental models	High material and manufacturing cost, Limited space flexibility due to panel rigidity, and there are durability concerns
	Inverter-driven compressors, efficient compressors	Adjust speed based on load, reducing start-stop cycles; higher efficiency, quieter operation	Common in newer high-efficiency refrigerators	Higher initial cost; limited retrofitting potential for old appliances, may require compatible control electronics
	Advanced controls, dynamic demand/response	Optimize energy use based on real-time conditions or grid signals; supports smart grid participation	Emerging in smart appliances; limited but growing	Dependent on smart meter/grid infrastructure, requires user trust and data privacy safeguards, higher software and integration complexity
	Door open warnings, removal of internal ice makers	Alerts users when doors are left open, preventing energy losses & reduces appliance complexity and standby energy	Widely available	Behavioural compliance (users may ignore warnings), ice maker removal reduces perceived convenience/utility for consumers
	Efficient lighting (LEDs) and fan-	Lower energy use, less heat than	LEDs are standard in	Minimal impact on total energy use

	assisted condensers	incandescent lighting & improve heat rejection and performance under high loads	modern appliances; fan-assisted features found in advanced models	individually, fans add minor mechanical complexity and noise
Cooking technologies	Induction Cooktops, Microwaves, Air Fryers	Induction: Approximately 84% efficiency, fastest heating, precise control.  Microwaves: Efficient for small portions; approximately 50–60% energy savings vs. oven.  Air Fryers: Smaller cavity, convection cooking with high efficiency	All widely available	Higher initial cost, requires compatible cookware (Induction), limited to specific food types/capacity (Microwaves/Air Fryers), not always suitable for larger meals/family cooking
	Efficient Oven Design / Manual Cleaning (vs. Pyrolytic)	Efficient insulation, better seals, smaller cavities which lead to reduced heat loss & manual cleaning avoids high-temp self-cleaning cycles (saves energy)	Available in energy-rated models	Consumers may prefer pyrolytic convenience despite energy cost, lack of awareness about energy-saving features
	Pre-heating Control / Temperature Monitoring / Pressure & Slow Cookers	Avoiding unnecessary pre-heating saves energy  Core temp monitoring avoids overcooking.  Pressure cookers reduce cook time/energy; slow cookers are low-wattage	Common consumer items	Requires behavioural change (e.g., skipping preheat), tech-savviness for temp monitoring (using probes or timers)
	Better Oven Door Insulation and Glazing	Double/triple glazed doors reduce heat loss,	Found in mid to high-end ovens	Cost premium for multi-glazed models, rarely considered a

		improve cooking efficiency		purchasing criterion by consumers
Ancillary Technologies	Efficient Dishwashers	Use less water and energy (especially with eco cycles and heat exchangers)	Wide; covered by EU energy labelling	Longer eco cycles may be less appealing, higher upfront cost for A+++ models, Behaviour (e.g., half loads) affects real-world performance
	Solar Electricity (PV) / Solar Thermal	PV supports all electric appliances; thermal systems preheat water	Fully commercial, with EU incentives	High installation cost, requires roof space/sunlight access, slow payback time without subsidies.
	IoT and AI for Real-Time Monitoring and Control	Enables energy optimization, predictive maintenance, and usage analytics	Increasing in smart homes; still niche	Data privacy and cybersecurity risks, complex installation and integration, user trust and acceptance vary

Source: ENOUGH's domestic roadmap

## Assessment for domestic roadmap

Most technologies available for decarbonizing domestic kitchens are already commercially available, particularly those at Technology Readiness Levels (TRL) 8–9, such as induction cooktops, inverter compressors, LED lighting, efficient dishwashers, and solar systems. However, widespread adoption is still limited by financial, behavioural, and regulatory barriers, especially in low- to middle-income households.

High upfront investment costs remain a key limitation for technologies such as induction cooking systems, VIP insulation, and solar integration, making them less accessible to financially constrained households. Even relatively inexpensive but impactful improvements such as switching to pressure cookers or reducing oven pre-heating, require consumer education and behavioural change, which are often overlooked in policy frameworks. Moreover, the benefits of electric technologies are highly dependent on national electricity grid decarbonization. In countries with high grid carbon intensity, switching to electric appliances may not yield immediate emissions reductions. As such, progress is tightly linked to broader energy system transformations.

There is also a lack of incentive structures and enforcement mechanisms to drive adoption. While EU energy labelling and eco-design directives exist, they do not always translate into consumer choices or drive manufacturer innovation at scale. To enable the transition toward low-carbon domestic kitchens, a coordinated policy, financial, and educational approach is required, especially one that ensures equity and access for vulnerable households.

To successfully decarbonize domestic kitchens and accelerate the adoption of energy-efficient technologies, governments and policymakers must implement a coordinated and inclusive strategy that integrates regulatory, financial, and educational interventions. A foundational step involves developing a unified national strategy for low-carbon domestic kitchens that aligns with broader EU climate targets. This strategy should include clear energy efficiency requirements and emissions reduction benchmarks tailored to the residential food storage and preparation sector.

To overcome the financial barriers that hinder widespread technology adoption, particularly among low-income households, public authorities should expand funding mechanisms. These may include grants or interest-free loans that help households invest in energy-efficient appliances such as induction cooktops, inverter-driven refrigerators, and high-efficiency dishwashers. In addition to direct financial support, fiscal incentives such as tax credits or VAT reductions can make high-performing appliances more accessible and appealing to the average consumer.

Minimum energy efficiency standards for domestic appliances must be strengthened, ensuring that new products meet stringent performance criteria and contribute to long-term emissions reductions. Simultaneously, early replacement programs should be promoted to phase out outdated and inefficient appliances, especially those containing high GWP refrigerants.

Consumer awareness is equally critical. Public education campaigns should focus on practical behavioural changes that reduce energy consumption, such as optimizing cooking methods (e.g., pressure or slow cooking), minimizing unnecessary pre-heating, and choosing appropriately sized appliances. These efforts should also demystify appliance energy labelling, enabling consumers to make informed purchasing decisions based on total lifecycle efficiency rather than sticker price alone.

Enforcement of existing labelling schemes and eco-design regulations must be improved through market surveillance and post-sale energy audits, ensuring compliance and consumer protection. Beyond enforcement, support for research and development is essential to foster the next generation of technologies—such as magnetic refrigeration, dynamic demand-response systems, and AI-optimized cooking environments. Public-private partnerships, innovation grants, and targeted pilot programs can play a key role in advancing these solutions.

The integration of renewable energy into domestic settings should also be facilitated. This includes policy frameworks and incentives to support the adoption of solar photovoltaic and solar thermal systems in residential buildings, alongside streamlined permitting processes and support for installation costs. These measures can enhance the climate benefits of electrification by ensuring that clean energy powers efficient appliances.

To enable smarter, more responsive energy use in kitchens, investments in digital infrastructure are needed. This includes developing data standards and interoperability frameworks that support the safe deployment of IoT and AI technologies while protecting user privacy. Open-access data platforms can allow households to benchmark energy use,

receive real-time efficiency recommendations, and empower consumers to actively manage their energy consumption.

Together, these measures create a robust foundation for decarbonizing domestic kitchens, enabling the sector to contribute meaningfully to national climate targets while enhancing energy resilience, reducing household costs, and promoting environmental justice.

## 5 EC FOOD 2030 AND TECHNOLOGY ROADMAPS

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The EC's Food 2030 Research and Innovation: Pathways for Action 2.0 report provides a comprehensive policy framework from the European Commission focused on transforming the food industry through research, innovation, and targeted funding. The EC sets the ambition to transform European food systems to be sustainable, healthy, climate-resilient, inclusive, and circular, that are covered in eleven pathways: (1) Governance for Food Systems Change; (2) Urban Food Systems Transformation; (3) Food from the Ocean and Freshwater Resources; (4) Alternative Proteins for Dietary Shift; (5) Food Waste and Resource-efficient Food Systems; (6) The Microbiome World; (7) Nutrition and Sustainable Healthy Diets; (8) Food Safety Systems of the Future; (9) Food Systems Africa; (10) Data & Digital Transformation; (11) Zero Pollution Food Systems. In the present report we aim to assess R&I priorities that are related to the food industry, thus within the ENOUGH project's scope. The policy gaps assessment was carried out only considering pathways that are related to the food industry: (1) Governance for food systems change; (2) Urban food systems transformation; (5) Food waste and resource-efficient food systems; and (11) Zero pollution food systems. From that, we assess them under the lens of policy, research, and technology to decarbonise the food industry.

### Pathway 1: Governance for food systems change

Governance is especially relevant to the accomplishment of the EGD and the F2F strategy to contribute to the future of resilient food systems. The report acknowledges substantial policy, financial, technological, environmental, and behavioural barriers to establishing a resilient and sustainable food system.

The governance pathway highlights the importance of investing in R&I in combination with support to evidence-based policymaking and implementation, adapt education programmes, skills and capacities, boost innovation and investment and encourage synergies and policy alignment. The document points the barriers and opportunities regarding the role of governance to promote political alignment.

What concerns industrial decarbonization, promoting R&I is fundamental to support the phase out of high pollutant technologies and to make new technologies available and competitive. The governance pathway invested EUR 51.5 million for projects within the Horizon 2020 and the Horizon Europe work programme within the period of 2020 to 2024. The topics addressed within such program are broad and cover several aspects of food-related sectors. Further investments are foreseen in several areas like food waste, bioeconomy, and to build a new "European innovation agenda" for regional innovation food

valleys. The document does not specifically mention actions to make the food industry net zero and although investments have contributed to advancing research and policy analysis across several spheres of food sustainability, industrial decarbonization remain underrepresented and lacking investment plan to support deployment in terms of planning, installation, technological integration, training, testing, monitoring, and economic viability in terms of competition.

Considering the limitations presented in the technology roadmaps, it is possible to point that considerable barriers are related to high installation costs, the need to considerable initial investments to integrate technologies to an existing operational system, and when technologies are not applied to all types of cold storage. Reducing GHG emissions in the food industry calls for precise investment plans while considering where energy can be used more efficiently, to integrate existing technologies, promote training, reporting and monitoring. Food-related political plans would gain to integrate food industry decarbonization strategies in a more comprehensive ways, by also including strategies to make clean technologies more competitive and available in the market.

## Pathway 2: Urban food systems transformation

This pathway is related to the way food is consumed in urban areas, which has direct synergies to the ENOUGH's domestic roadmap. About 80% of global food production is consumed in urban areas, a fact that suggests significant capacity for change. In this pathway, nutrition and dietary shifts are core priorities even for climate and sustainability co-benefits.

A total of EUR 70.8 million were allocated to projects in areas policy creation and coherence, food waste, change in diets and to urban– rural governance and awareness raising. Future investments target actions to improve urban-rural interface to improve urban food system resilience with the use of big data, support local entrepreneurship, knowledge integration and training, and investing in opportunities to redesign urban spaces. The document would gain to integrate aspects about domestic-related cooking and refrigeration technologies, which are important sources of household GHG emissions. Following the domestic roadmap, several technologies are emerging but still face high initial and installation costs, and difficult integration to a pre-established system. Consumers' awareness and behaviour towards energy-saving features.

## Pathway 5: Food waste and resource-efficient food systems

Food systems account for 30% of energy consumption, which highlights the importance of increasing resource efficiency also as means to enhance economic performance. Although this pathway mainly focuses on natural resources such as water, soil, and biodiversity, energy could be integrated and analysed across all FSC stages. The climate change-related co-benefits point to the need to reduce pressure on natural resources especially water, soil, and energy, thus making reference to GHG emissions reduction.

A total of EUR 170 million were allocated for the Horizon 2020 and Horizon Europe in areas such as food loss and waste in particular data collection, reporting, methodologies and tools.

Future investments are foreseen to projects about circularity in food systems, data quality and harmonization, resource-smart technologies, and targeting stakeholders regarding food choices.

The EC priorities to promote resource-efficient food systems shall consider energy related targets and increasing investments to deploy energy-efficient technologies. Similarly to previous pathways, opportunities to reduce GHG emissions and energy use in food industries are not comprehensively considered in the Food 2030 report, a fact that hinders considerable opportunities to phase out fuel-based resources use. Moreover, investments shall not only consider the development of energy-efficient technologies, as well as they should enable sustainable options to be more competitive in the market when compared to available technologies.

### Pathway 11: Zero pollution food systems

This pathway considers the impact generated from pollutants when producing, processing, and consuming food. Two sources of pollutants are considered: environmental pollution into soil, water, and air, and food contamination. The climate and sustainability co-benefits highlight the need to mitigate climate change by reducing GHG emissions, however, the topic is broader and has strong interplays with other sectors.

Investments accounted over EUR 190 million to address issues such as plastic pollution and pollution with pesticides and fertilisers. Future research aims to target R&I actions to assess food-related pollution sources, methods to reduce them, and their monitoring.

Following the roadmaps, there are already a high amount of technologies available to improve energy systems in the food industry. Nevertheless, more investments to integrate such technologies with existing structure are timely. Moreover, the continuous development of further energy-efficient technologies is only possible with increasing funds to research and development and innovation in FSC stages from farm to fork.

## 6 CONCLUSION

Achieving deep decarbonization across all stages of the food value chain, including refrigerated transport, cold storage infrastructure, domestic kitchens, and related logistics, demands a systematic, cross-sectoral approach that integrates technological innovation with coherent policy frameworks and targeted financial mechanisms. Although mature, energy-efficient technologies are available, their adoption is hindered by high upfront costs, fragmented governance, and a misalignment between policy instruments and real-world market conditions.

A critical difficulty identified throughout the value chain is the lack of comprehensive, enforceable policy frameworks that effectively support the deployment and integration of low-emission technologies in the food industry. Although instruments such as energy labelling schemes, performance standards, and fiscal incentives exist, they are often insufficiently applied, not enforced, or inadequately scaled. SMEs are particularly

disadvantaged, facing limited access to financing and lacking the institutional capacity to navigate complex regulatory and funding landscapes.

There are also notable policy gaps in the operationalization of energy performance standards, especially in the transport and cold storage sectors. Minimum energy efficiency requirements for refrigeration units and insulation systems are either underdeveloped or weakly enforced, with compliance mechanisms such as inspections and monitoring often lacking the necessary resources or rigor. In the domestic context, despite the technological readiness of efficient appliances, regulatory instruments often fall short to incentivizing early replacement or ensuring equitable access for low-income households.

Furthermore, existing research and innovation R&I strategies outlined in the European Commission's Food 2030 pathways do not sufficiently prioritize industrial decarbonization, particularly regarding the deployment, integration, and scaling of clean technologies in the food industry. While significant investments have targeted areas such as circularity, food waste, and urban food systems, energy efficiency and emissions reduction remain underrepresented, both in funding allocation and in strategic emphasis. Addressing these structural gaps requires the development of a coordinated policy architecture that explicitly embeds decarbonization objectives into regulatory, financial, and institutional frameworks. This should include:

- The establishment and enforcement of mandatory minimum energy performance standards for transport refrigeration, cold storage, and domestic appliances.
- The design of dedicated financial instruments to facilitate access to capital for SMEs and low-income households, such as targeted grants, concessional loans, and tax-based incentives.
- The implementation of robust compliance mechanisms, including systematic monitoring, verification, and enforcement protocols.
- Investment in training and capacity-building programs across the value chain to support the workforce transition to low-emission operations.
- And a recalibration of R&I priorities to ensure that funding mechanisms directly support the deployment, integration, and market competitiveness of decarbonization technologies.

Without such coordinated and strategic interventions, achieving carbon neutrality in the food sector will be at risk. Ensuring policy coherence, strengthening institutional capacity, and providing targeted financial support are essential to unlocking the sector's full mitigation potential and aligning it with broader climate and sustainability goals at both national and EU levels.

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