PROJECT ACRONYM	ENOUGH
PROJECT TITLE	European Food Chain Supply to reduce GHG emissions by 2050
PROJECT COORDINATOR	SINTEF OCEAN
PROJECT DURATION	2021-2025

D9.6

Final summary of the ENOUGH project: actions for carbon neutrality in food systems

PROJECT NO: 101036588

TYPE OF ACTION: IA (INNOVATION ACTION)

CALL: H2020-LC-GD-2020-4

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588

DOCUMENT INFORMATION

DELIVERABLE NO.	D9.6 Final summary of the ENOUGH project: actions for carbon neutrality in food systems
DISSEMINATION LEVEL	Public
WORK PACKAGE	WP9
TASK	T9.3 Monitoring of project activities and work progress
LEAD BENEFICIARY	SO
CONTRIBUTING BENEFICIARIES	IIR, LSBU, UoB, INRAE, UNIVPM, CNR, UGOE
DUE DATE OF DELIVERABLE	30.09.2025
ACTUAL SUBMISSION DATE	30.09.2025

DOCUMENT HISTORY

Version	DATE	CHANGE HISTORY	AUTHOR	BENEFICIARY
1	24.09.2025		Kristina N. Widell, all WP leaders	SINTEF Ocean

QUALITY ASSURANCE, STATUS OF DELIVERABLE		
ACTION	PERFORMED BY	DATE
Reviewed	All WP leaders	29.09.2025
Approved	All WP leaders	29.09.2025
Uploaded to SyGMa (Coordinator)	Kristina N. Widell	30.09.2025

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EXECUTIVE SUMMARY

The ENOUGH project, funded by the European Commission, has been running for four years, from October 2021 to September 2025. Its goal was to support the transition to a climate-neutral food supply chain, with a particular focus on the cooling and heating processes involved.

The project aimed to contribute to the EU Farm to Fork Strategy by identifying how the food sector can:

1. Reduce GHG[1]-emissions by at least 55% by 2030 compared with 1990 levels.
2. Achieve climate neutrality for food businesses by reducing energy use and increasing energy efficiency by 2050.
3. Improve the overall integrated sustainability of food systems (including social/health, climate/environmental and economic aspects) whilst at the same time meeting societal goals.
4. Increase awareness among policy makers, businesses, investors, entrepreneurs, institutions, stakeholders and citizens of selected innovative systemic solutions and their potential for uptake at EU scale.

The consortium consisted of 30 partners from 12 European countries. Despite its size, and some changes along the way, collaboration has been excellent, leading not only to significant impact for the sector but also to life-long friendships.

This is the final summary report. It is intended to give new readers insight into the project, and to provide those already familiar with ENOUGH a clear overview of its outcomes and guidance on where to find further information.

The ENOUGH project has addressed key challenges in decarbonising the European food sector, which comprises over 300,000 enterprises, the vast majority being small to medium-sized. With food and agriculture responsible for around 34% of global greenhouse gas (GHG) emissions, the project has shown that substantial reductions are achievable through targeted innovation, systemic change, and stakeholder engagement.

ENOUGH has explored advanced technologies and business models to overcome financial and operational barriers, particularly for smaller actors. It has demonstrated that emissions can be significantly reduced by shifting to natural refrigerants, integrating heating and cooling systems, and adopting alternative freezing and storage methods. These solutions not only improve energy efficiency but also extend shelf life and reduce waste.

Digital tools developed within the project support emission tracking, scenario modelling, and collaborative decision-making. Case studies have highlighted the impact of sourcing choices and transport modes, while regional differences in consumer engagement point to the need for tailored strategies.

The project concludes that climate neutrality in the food supply chain by 2050 is feasible, with a 55% reduction possible by 2030. Achieving this will require coordinated policy support, investment in high-efficiency technologies, and widespread adoption of sustainable practices across the sector.

Most importantly, **urgent and coordinated action** is needed now, involving farmers, operators, processors, retailers, policymakers and us consumers, to accelerate decarbonisation and secure a just and achievable path to climate neutrality.

[1] GHG: Greenhouse gases – gases in the atmosphere that trap heat and contribute to global warming. The most common include Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

Deliverable 9.6

1 INTRODUCTION

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Section 2 explores key challenges in the food supply chain and how the ENOUGH project has contributed to addressing them.

Section 3 provides a summary of each work package and recommendations.

Section 4 describes project management, including collaboration with other initiatives.

Section 5 covers dissemination activities and external communication.

Section 6 presents conclusions and suggestions for future work.

More details and photos, including publications and presentations are available at the ENOUGH webpage enough-emissions.eu.

2 CHALLENGES IN THE FOOD SUPPLY CHAIN AND ENOUGH'S CONTRIBUTIONS

2.1 A highly diversified sector

The European food sector is highly diverse, comprising approximately 304,120 enterprises, of which 99.2% are small- to medium-sized enterprises (SMEs). Collectively, these businesses employ more than 4.7 million people and has a turnover of €1,196 billion[2]. This diversity presents a major challenge for decarbonisation, as it encompasses a wide range of subsectors, from primary production and processing to packaging, retail, catering and consumers.

Reaching and effectively communicating with such a fragmented sector is difficult. Many SMEs face barriers to adopting low-emission technologies, including a lack of time, staff resources, and initiative fatigue; limited financial capacity for investment; insufficient understanding of environmental risks and benefits; low levels of expertise and confidence; poor access to appropriate information; and the perception that environmental activities are peripheral to core business operations (Constantinos, 2010)[3]. These barriers apply not only to carbon reduction but also to water, resource, and energy-saving measures. The ENOUGH project has responded to these challenges by demonstrating technologies at TRL[4] 5–7, showcasing their feasibility, financial viability, and reliability across different subsectors. Through strong engagement with industry associations, ENOUGH has also supported dissemination and uptake of solutions throughout the sector.

ENOUGH's contributions through activities in different work packages (WPs) :

- WP1 has demonstrated how behavioural, regulatory, and technological drivers differ across countries, highlighting the need for policies and strategies that reflect national contexts.
- WP2 has shown that each food chain sector requires a dedicated roadmap, since the potential for emissions reduction depends strongly on the technologies available and their readiness levels.
- WP3 has found that traditional equipment ownership models pose significant barriers for small and medium-sized enterprises due to high upfront costs and limited access to finance. In response, ENOUGH has explored innovative business models—such as servitisation, performance-based approaches, and Power Purchase Agreements—which offer more flexible cost structures, improved system efficiency, and potential for energy savings.
- WP4 has used case studies to demonstrate how geographic sourcing decisions—such as local production versus imports—can significantly alter the carbon footprint of food products.
- WP5 has shown that the complexity of actors and data systems in the supply chain requires adaptable digital infrastructures. The SDS framework developed within ENOUGH enables multi-party collaboration, digital twin modelling, and flexible integration of third-party applications.
- WP6 has provided 21 technology demonstrators at TRL5–7, ranging from dairies and seafood freezing to refrigerated transport and retail systems, showing technical feasibility, financial viability, and reliability.

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[2] https://www.fooddrinkeurope.eu/wp-content/uploads/2025/01/FoodDrinkEurope-Data-Trends-2024.pdf

[3] Constantinos, C; Sørensen, S-Y; Larsen, P-B; Alexopoulou, S; et al. (2010) SMEs and the environment in the European Union, PLANET SA and Danish Technological Institute, Published by European Commission, DG Enterprise and Industry.

[4] TRL (Technology Readiness Level) is a scale used to assess the maturity of a technology, ranging from TRL 1 (basic principles observed) to TRL 9 (fully proven in operational use). It helps compare how close different technologies are to market deployment.

- WP7 has revealed regional disparities in consumer and civic engagement, with North-Western Europe showing greater uptake of sustainability measures compared to South-Eastern regions—emphasising the importance of place-based strategies.
- The project partners have actively disseminated results to a wide range of stakeholders, including the general public. Early engagement was essential, as reaching diverse audiences takes time and sustained effort.
- Joint webinars and workshops with other projects have enabled outreach to a broader network, including individuals and organisations not typically within our sphere of contact.

Altogether, ENOUGH has demonstrated that while the food sector's diversity poses clear challenges to decarbonisation, it also opens opportunities for tailored, sector-specific solutions. By combining technology demonstrations, roadmaps, and digital decision-support tools, ENOUGH has provided a foundation for reducing GHG emissions across Europe's food supply chain, while ensuring strategies are adapted to local contexts, technologies, and consumer behaviours. The project has collaborated with a range of actors, including both small and large entities, demonstrating that the proposed solutions are adaptable across the diverse food value chain.

2.2 One third of global greenhouse gas emissions come from the food sector

Food and agriculture are responsible for about 34% of global greenhouse gas emissions (Crippa et al., 2021)[5]. Post-farm gate activities — including processing, packaging, transport, storage, retail, catering, and home consumption — are estimated to account for around 11% of total emissions (FAO, 2023)[6]. Emissions from the food supply chain emanate from energy consumption (fuel and electricity), the leakage of the high global warming potential (GWP) refrigerants and methane from the wasted food in landfill.

Emissions are commonly categorised into three scopes, as defined by the Greenhouse Gas Protocol[7].

- Scope 1 refers to direct emissions from sources owned or controlled by the entity. These include emissions from on-site fuel combustion for electricity and heating (e.g. food processing), the manufacture or processing of chemicals and materials (e.g. food packaging), and the operation of machinery, primarily vehicles (e.g. transport). Scope 1 also includes fugitive emissions, which in the food sector are mainly due to refrigerant leakage.
- Scope 2 covers indirect emissions from the generation of purchased electricity consumed by the entity. Although the electricity is produced off-site, its use contributes to the entity's carbon footprint.
- Scope 3 includes all other indirect emissions that occur as a consequence of the entity's activities, but from sources not owned or directly controlled. This can include emissions from waste disposal, supply chain operations, and product use.

Despite the large scale of the emissions, these figures remain poorly quantified and lack sector-specific detail. Establishing accurate baselines and projections has therefore been a central task for the

5 Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N. & Leip, A. (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food, 2, pp. 198–209.
6 FAO (2023). Agrifood systems and land-related emissions: Global, regional and country trends 2001–2021. FAOSTAT Analytical Brief 73.
7 World Resources Institute & World Business Council for Sustainable Development (2004). The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition). Available at: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

ENOUGH project, which has quantified emissions for 1990 and 2019, and projected trajectories to 2030 and 2050.

According to the International Institute of Refrigeration (IIR)[8], nearly half of all food products require refrigeration at some point, highlighting the critical role of cold chain infrastructure. Refrigeration is both indispensable and energy-intensive, making it a key hotspot for intervention. ENOUGH has assessed emissions across all stages of the supply chain, identifying where interventions can deliver the greatest impact.

ENOUGH's contributions:

- WP1 quantified food-related emissions across European countries, showing that food accounts for 10–24% of national GHG emissions. Modelling indicated that replacing meat with alternative proteins could reduce emissions by up to 32%.
- WP2 produced sectoral roadmaps showing that significant reductions are achievable by 2050, particularly if mature, high-TRL technologies are widely deployed.
- WP3 modelled energy use in the European food sector, estimating consumption at 1,211 TWh in 2019, with over 70% derived from oil and gas — highlighting the urgent need for an energy transition.
- WP4 demonstrated the mitigation potential of operational changes. Case studies showed that switching frozen salmon transport from air to sea reduced emissions by 90%, while advanced packaging technologies achieved savings of up to 72%.
- WP5 advanced digital infrastructures for emission tracking and optimisation. The SDS platform, using digital twins and blockchain-enabled transparency, allows more accurate monitoring of energy use and emissions, helping stakeholders identify hotspots and opportunities for reduction.
- WP6 demonstrated that available technologies could reduce emissions by up to 50%. Absorption–compression heat pumps and CO_2-based refrigeration systems showed high efficiency and low environmental impact across demonstrator sites, although uptake remains constrained by fragmented infrastructure and limited awareness. Substantial emissions reductions, up to 50%, can be achieved using technologies that already exist.
- WP7 identified a lack of alignment between current policies and the decarbonisation potential of available technologies. It also highlighted the need for stronger consumer engagement and behaviour change to complement technological advances.
- The project has demonstrated that achieving a climate-neutral food supply chain by 2050 is feasible, with a 55% emissions reduction possible by 2030. The necessary technologies are either already available or at a relatively high Technology Readiness Level (TRL). However, reaching these targets requires a shift away from fossil fuel-based energy consumption, the adoption of natural refrigerants throughout the supply chain, installing energy efficient equipment and the implementation of incentives to reduce food loss and waste.

2.3 Advanced solutions are needed to reduce emissions

The food industry has already made notable progress in reducing energy consumption. FoodDrinkEurope estimates a 22% reduction between 1990 and 2012[9], and a further 12% between

8 International Institute of Refrigeration (IIR). (2025). The role of refrigeration in the global economy (3rd edition). 60th IIR Technical Brief on Refrigeration Technologies. Paris: IIR. https://iifiir.org/en/news/international-institute-of-refrigeration-iir-releases-new-technical-brief-the-role-of-refrigeration-in-the-global-economy-3rd-edition

9 FoodDrinkEurope. (2015) A Time to Act. Climate Action and the Food and Drink Industry. Retrieved from: https://www.fooddrinkeurope.eu/uploads/publications_documents/FoodDrink_Europe_Climate_Action_Brochure.pdf

2008 and 2017[10], achieved while production levels continued to rise. Much of this progress has been driven by incremental optimisation measures, including improved maintenance and operational practices. However, further reductions will require advanced technologies and systemic change. For example, in the UK food sector, boilers alone account for around 54% of total energy use (DECC, 2015)[11], highlighting the urgent need for low-emission alternatives.

These challenges present opportunities to deploy integrated and innovative solutions. Heating and cooling systems can be combined, waste heat recovered, and renewable energy sources, such as solar PV, wind, and geothermal, which can be incorporated into industrial operations alongside energy and thermal storage systems. Reducing emissions across the food sector therefore requires more than incremental improvements: it demands the large-scale adoption of more complex, scalable solutions throughout the supply chain.

ENOUGH's contributions:

- WP1 and WP2 modelling show that substantial reductions in greenhouse gas emissions are achievable through high-TRL technologies, particularly in refrigerated transport, cold storage, and food processing. WP2 roadmaps demonstrate that near net-zero emissions are possible by 2050 if the best available technologies are consistently applied.
- WP3 identifies key opportunities for advanced solutions, including high-efficiency refrigeration, solar-assisted systems, and digital energy management tools. WP3 also highlights business models such as servitisation and performance-based contracting, which can reduce financial barriers for SMEs.
- WP4 demonstrates the potential of waste heat recovery, advanced packaging, and thermal energy storage (TES) to reduce emissions across food chains. The ENOUGH platform developed under WP4 supports stakeholders by simulating scenarios, identifying emissions hotspots, and testing optimal decarbonisation strategies.
- WP5 contributes to advanced solutions through digital innovation, including blockchain, mixed reality, and distributed decision-making. The SDS platform integrates digital twins with behavioural nudging and token-based incentives, fostering collaboration and transparency across diverse supply chain actors.
- WP6 provides proof-of-concept demonstrations of market-ready solutions (TRL 7–9), including:
  - natural refrigerants and CO_2 plate freezers for seafood and meat processing;
  - TES and heat recovery systems for dairies and retail;
  - superchilling and freeze-drying to extend shelf life and reduce food waste;
  - digital monitoring and optimisation tools, tailored to SMEs.
- WP7 highlights that policy frameworks are not yet fully aligned with the decarbonisation potential of these solutions, which risks slowing their deployment. Without coordinated support — including regulation, financing, and workforce training — innovation uptake may remain fragmented and limited to niche markets.
- The ENOUGH project has advanced innovative solutions across the food supply chain, particularly in cooling and freezing technologies. By pushing development along the TRL scale, the project has demonstrated how integrated heating and cooling systems can significantly reduce energy demand, though they also introduce greater system complexity. ENOUGH has

[10] FoodDrinkEurope. (2020). Climate Change Position Paper. Retrieved from: https://www.fooddrinkeurope.eu/uploads/publications_documents/Climate_change_-_position_paper.pdf
[11] Department of Energy and Climate Change. (2015). Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050: Food and Drink. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416672/ Food_and_Drink_Report.pdf

gone beyond conventional efficiency measures, exploring alternative freezing methods that require less energy, and investigating controlled atmosphere storage to extend shelf life. These approaches often depend on digital infrastructure and smart control systems. Importantly, the project has actively engaged with industry and society to identify practical, scalable actions that can be taken to improve sustainability in food chain cooling and freezing.

Beyond technological innovation, behavioural change is also critical. WP1 and WP7 show that dietary shifts, such as replacing meat with alternative proteins, can reduce emissions by up to 32%. However, uptake depends on consumer trust, affordability, and awareness.

3 SUMMARY OF WORK PACKAGES AND RECOMMENDATIONS

3.1 WP1: Baseline (1990) current (2019) and future (2030 and 2050) carbon emissions

The ENOUGH project developed two independent models to assess and forecast greenhouse gas emissions across the European food supply chain. Historical emissions for 1990 and 2019 were analysed, and predictive models were created for 2030 and 2050. Food production and consumption was found to account for between 10–24% of total emissions in selected European countries, highlighting the urgent need for decarbonisation in the sector.

System Dynamics and Linear Programming models were used to explore meat consumption trends and design optimised diets that maintain nutritional adequacy while incorporating alternative proteins. These models demonstrated that replacing meat with suitable alternatives could reduce emissions by up to 32%.

A cross-national model was also developed, integrating behavioural, regulatory and technological drivers. Under a Low Emissions scenario, the model showed a potential reduction of over 60% in cumulative emissions, with electricity grid decarbonisation, oil and gas substitution, and energy labelling identified as the most impactful interventions.

The models have attempted to overcome some of the limitations that the existing database on food chain emissions have regarding data granularity, uncertainty and replicability.

These findings provide a robust evidence base for guiding the transition to net-zero food systems.

3.1.1 Recommendations for industry

- Prioritise low carbon electrification and invest in energy-efficient technologies across the food supply chain.
- Innovate and diversify alternative protein products to better meet nutritional needs and consumer preferences.
- Engage with modelling tools to assess the impact of operational changes on emissions and to prioritise reduction measures with highest emission savings potential.

3.1.2 Recommendations for policy makers

- Support a gradual transition from meat to nutritionally appropriate alternative proteins through targeted policies and incentives.
- Strengthen climate-aligned regulations, including energy labelling and support for grid decarbonisation.
- Use integrated modelling frameworks to inform national and regional food system strategies.
- Provide electrical infrastructure to allow the industry to move away from fossil fuels.
- Make electricity cheaper rather than more expensive than fossil fuels to provide incentive to electrify.
- Support and advocate for funding of initiatives aimed at reducing GHG emissions across the food supply chain, especially those focused on improving cold chain infrastructure, energy efficiency, and low-emission transport and logistics solutions.

3.1.3 Recommendations for society

- Choose climate-friendly diets and make informed food choices. This includes shifting towards foods with lower climate impact, such as alternative proteins, and considering sustainability when purchasing, storing and consuming food.
- Avoid and minimise food waste by applying better storage, meal planning and consumption practices to ensure resources are not lost.
- Use available technologies efficiently by optimising the operation of household and retail equipment such as refrigeration and storage systems to cut energy use and emissions.

3.1.4 Key publications

- Mehta, S., Foster, A., Rosetti, A., Bengsch, J., Köster, L., Evans, J., Allouche, Y., Widell, K.N. and Iordan, C.M., 2024. A comparative assessment of food chain emissions from Norway, UK, Germany and Italy. In: Proceedings of the 8th IIR International Conference on Sustainability and the Cold Chain (ICCC 2024). DOI: 10.18462/iir.iccc2024.1100
- A comprehensive top-down method to determine whole food chain emissions in European Economic Area countries. Foster, A., Rosetti, A., Mehta, S., Bengsch, J., Köster, L., Evans, J., Widell, K.N. and Iordan, C.M., Delahaye, A., Allouche, Y. Submitted to Journal of Cleaner Production. [not yet published].
- Projected GHG emissions, considering behavioural, regulatory and technological drivers, between 2019 and 2050 in the post-harvest food chain in 10 European countries. Foster, A., Weize, W., Tsiamas, K., Feng, Y., Lamidi, R., Naseh Moghanlou,.L., Singh, A., Iordan, C.M., Mehta, S., Evans, J., Wang, X. planned to submit to Journal of Nature Food. [in preparation].
- Integration of System Dynamics Modelling and Optimization Methods to Define a Sustainable Diet Balancing Emissions and Nutrition While Considering Economic Elasticity and Social Acceptance. Naseh Moghanlou,.L., Evans, J., Foster, A., Tsiamas, K., Singh, A., Wang, X. planned to submit to Journal of Sustainable Production and Consumption. [in preparation].

3.2 WP2: Technology roadmaps to decarbonise the European food chain

Roadmaps were created for 6 food chain sectors to help identify how each sector can decarbonise and rapidly reach net zero. As part of the work, independent reviews of different technologies/strategies were used to guide industry and end user to make the best-informed choices on how to reduce greenhouse gas emissions and energy consumption. Scope 1 and 2 emissions were covered which encompass emissions from leakage of refrigerants and emissions from direct fuel use (e.g. gas) and indirect emissions from the electrical grid.

The most appropriate technologies and strategies with the most potential to reduce GHG emissions were selected from the reviews. The promising technologies that had a high TRL were modelled and their potential to reduce emissions in each food sector assessed. GHG emissions from many lower TRL technologies were excluded as often they were difficult to quantify and many had very varied application times and the claimed savings often varied widely.

Results from the reviews and modelling identified routes for each food chain sector to reduce emissions and enabled the creation of a roadmap through to 2050. In all sectors there was considerable potential to reduce GHG emission by 2050. The table on the next page presents a summary of each road map and the potential to reduce GHG emissions.

3.2.1 Recommendations to industry

- A number of relatively simple and low-cost options to decarbonise are available in all sectors examined.
- Options are available to retrofit or for new systems.
- It is possible to get very close to net zero in 2050 if apply best technologies.

3.2.2 Recommendations to policy makers

- Electrification of systems is an extremely important part of decarbonisation. Therefore, the grid needs to decarbonise at the rates anticipated by Governments.
- Phasing out F-gasses and transitioning to natural refrigerant alternatives is essential.
- Interactions between technologies occur, so it is important that policy development carefully considers any potential unintended consequences.

3.2.3 Recommendations to society

- Implementing technologies and strategies now enables earlier carbon reductions and results in lower overall emissions.
- Location and timing influence the selection of equipment and the extent of the overall benefits achieved.

Table 1. A summary of each road map and the potential to reduce GHG emissions

	Food processing	Cold storage	Transport	Retail	Food service	Domestic
Technologies	54	30	29	95	60	54
Model	Bespoke	ice-e	CNR	EnergyPlus	EnergyPlus	EnergyPlus
Facility	Typical: Meat Fish Dairy plant Ready prepared	43,758 m^3 chilled store 60,760 m^3 frozen store	Long haul MT Long haul LT Regional transport MT Regional transport LT Last mile multi-temp Last mile frozen TES	2,100 m^2 (medium) 600 m^2 (small) store	High usage QSR Medium usage QSR	Typical kitchen
Scenarios	Beef/pork/poultry abattoir: efficient chilling, heat pumps, air compressors, green hydrogen or biomethane, RES (solar) Pelagic fish processing: refrigeration system efficiency, improved freezing, brine freezing Milk: heat recovery/energy integration, efficient equipment and machinery, process optimisation and control, building and infrastructure efficiency Fish fingers, beef casserole: HTHP, electrification, refrigeration efficiency, use of waste heat, alternative cooking	Retrofit: Vestibule More efficient condenser and fans Maintenance RES (solar) New store: High efficiency compressor Refrigerants (R744)	Curtains (60% Inf.) Insulation (k=0.3) R744 unit R290 unit Curtains (60% Inf.)+insulation (k=0.3)+R744 unit Curtains (60% Inf.)+insulation (k=0.3)+R290 unit Electrification	Minor retrofit: Store dead band HFO (small store) Doors chilled cabinets Major retrofit: Heat pumps 20% better cabinets RES (solar) R744	Retrofit: Increase dead band by 2K Economiser in HVAC Higher efficiency equipment Low GWP refrigerant Maintenance/ operational practices RES (solar PV)	ASHP Resistive cooking Induction cooking Efficient cooking appliances Efficient refrigeration Efficient dishwasher
GHG savings (now)	n/a	Retrofit (combined): Chilled: 11-67%. Frozen: 60-80% New (combined): Chilled: 18-92%. Frozen: 31-69% Retrofit+new: Chilled: 66-93%. Frozen: 72-94%	7-100%	Minor retrofit (combined): Medium: 31%. Small: 51% +Major retrofit (combined): Medium: 65%. Small: 45%	Retrofit (combined): New (combined): High usage: 40-44%. Medium usage: 42-52%	-38% (Kaunas) - 65%
GHG savings (2050)	Meat: 70-100% Fish: up to 100% Milk: up to 100% Prepared: 12-91%	Up to 100%	Up to 100%	Up to 100%	Up to 100%	Up to 100%

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588

3.2.4 Key publications

- FOSTER A., BROWN, T. AND EVANS, J. Carbon emissions from refrigeration used in the UK food industry, International Journal of Refrigeration, 2023, https://doi.org/10.1016/j.ijrefrig.2023.01.022.
- EID, E., FOSTER, A., EVANS, J., LEDUCQ, D., NDOYE, F. AND ALVAREZ, G. Modelling energy consumption in supermarkets to reduce energy use and greenhouse gas emissions using EnergyPlus. IIR International Congress of Refrigeration (IRC), 2023.
- EID, E, FOSTER, A, ALVAREZ, G., NDOYE, F-T., LEDUCQ, D, and EVANS, J. Modelling energy consumption in a Paris supermarket to reduce energy use and greenhouse gas emissions using EnergyPlus. International Journal of Refrigeration. 2024.
- EID, E., FOSTER, A., EVANS, J., CAMPBELL, R. and ALVAREZ, A. Modelling of energy use and greenhouse gas emissions from a quick service restaurant. ICCC2024, 8th IIR International Conference on Sustainability and the Cold Chain, June 9-11, 2024. Tokyo, Japan.
- FOSTER, A. and EVANS, J. Commercial professional and domestic refrigeration equipment efficiency in the UK; current and future trends. ICCC2024, 8th IIR International Conference on Sustainability and the Cold Chain, June 9-11, 2024. Tokyo, Japan.
- EVANS, J. Keynote lecture: Carbon emissions from the food chain and how to mitigate them. ICCC2024, 8th IIR International Conference on Sustainability and the Cold Chain, June 9-11, 2024. Tokyo, Japan.

3.3 WP3: Energy, behaviour, finance

WP3 focused on developing practical strategies to decarbonise the European food supply chain by analysing technological, financial and behavioural pathways. The work included the development of an energy roadmap based on 2019 baseline data, alongside a comprehensive assessment of financial requirements and business models to support the uptake of low-carbon technologies.

The roadmap quantified energy use across selected European countries, showing that the food sector consumed approximately 1,211 TWh of final energy in 2019, with over 70% derived from oil and gas. By 2050, oil and gas use could be reduced by more than 80%, with electricity accounting for over 60% of the energy mix. Refrigeration and cold chain technologies were identified as among the most energy-intensive operations. Upgrades such as CO_2-based refrigeration, high-efficiency fans, variable speed drives, vacuum insulation and smart controls could reduce electricity use by 15 to 17%, delivering over 25 TWh in annual savings in countries like Germany and France.

Heating, largely gas-fired in processing and catering, could be decarbonised through heat pumps, hybrid ovens and solar-assisted systems, achieving emissions reductions of 30 to 50%. In refrigerated freight, fuel use could be reduced by 10 to 47% through electric and hydrogen vehicles, aerodynamic retrofits, energy recovery systems and zero-GWP refrigerants. Digital tools such as IoT-based energy management systems, real-time analytics and predictive maintenance were shown to reduce energy consumption by 5 to 10%, particularly in refrigeration and food processing. On-site renewable generation, including solar PV, biogas and geothermal, could meet up to 70% of a facility's demand when combined with battery and thermal storage.

Behavioural shifts also play a critical role. Increased use of frozen foods and plant-based diets could reduce household food waste by up to 47% and lower system-wide energy demand by as much as 40%. A broad literature review and survey conducted across five European countries identified key behavioural drivers and public perceptions related to alternative proteins, food waste reduction, frozen food, online platforms and food packaging. The findings revealed both similarities and regional

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differences in consumer attitudes, which are essential for shaping future scenarios and policy interventions.

In parallel, WP3 reviewed academic literature and industry documents to categorise existing business models in the food and energy sectors. This analysis identified the main features, financial mechanisms, enablers and barriers associated with each model. Traditional equipment ownership models were found to pose significant barriers due to high upfront costs and limited access to finance. In response, innovative models such as servitisation (e.g. cooling as a service, energy as a service), performance-based approaches and Power Purchase Agreements were explored. These models offer potential for energy savings, improved system efficiency and more flexible cost structures, particularly for small and medium-sized enterprises.

The assessment also examined the driving forces behind business model innovation and evaluated sustainability performance across environmental, social and economic dimensions. Financing mechanisms such as concessional loans, blended finance and public-private partnerships were identified as key enablers. Case studies from Europe, India, Bangladesh and Nigeria demonstrated the operational feasibility and adaptability of these models in cold storage and food logistics.

Ultimately, the findings from WP3 provide a coordinated foundation for reducing emissions across the food sector. The integration of technological innovation, behavioural change and financial strategy is essential to meet the EU's target of a 55% net emissions cut by 2030 and achieve climate neutrality by 2050.

3.3.1 Recommendations for industry

- Prioritise energy-efficient and low-emission technologies in key areas such as refrigeration, heating and transport.
- Adopt innovative business models such as servitisation (e.g. cooling as a service, energy as a service) and performance-based approaches to reduce upfront investment and improve access to clean technologies.
- Invest in digital tools including IoT-based energy management systems, predictive maintenance and real-time analytics to optimise energy use and reduce operational costs.
- Explore on-site renewable energy generation (e.g. solar PV, biogas, geothermal) combined with storage solutions to increase energy independence and reduce reliance on fossil fuels.
- Engage with financial mechanisms such as blended finance and public-private partnerships to support long-term decarbonisation strategies, especially for small and medium-sized enterprises.

3.3.2 Recommendations for policy makers

- Implement minimum energy performance standards for food sector technologies, including refrigeration, heating and transport systems.
- Provide fiscal incentives such as tax credits, concessional loans and simplified permitting processes to accelerate the adoption of low-carbon technologies.
- Support the development and scaling of innovative business models through targeted regulation and funding schemes.
- Align climate, energy and food policies to ensure coordinated governance and remove barriers to technology deployment.
- Promote behavioural change through public awareness campaigns and education initiatives, focusing on sustainable food choices and energy-saving practices.

3.3.3 Recommendations for society

- Adopt sustainable consumption habits, including increased use of frozen and plant-based foods, which can reduce food waste and lower energy demand.
- Engage with digital platforms and eco-labelling schemes to make informed choices about food products and their environmental impact.
- Support community-level initiatives and cooperatives that promote energy-efficient practices and local food systems.
- Recognise the role of individual behaviour in achieving climate goals and participate in educational programmes that raise awareness of food system sustainability.
- Advocate for inclusive policies that ensure clean technologies and sustainable food options are accessible to all, regardless of income or location.

3.3.4 Key publications

- Thermal energy storage as a service business model for food supply chain decarbonisation. Proceedings of the 16th IEA ES TCP International Conference on Energy Storage (ENERSTOCK 2024). p 532-533

3.4 WP4: Integration of heating, cooling, AC, thermal symbiosis and energy storage within and between sectors

WP4 focused on the conceptual development and practical application of the ENOUGH tool, a web-based simulation platform designed to model food supply chains and assess associated greenhouse gas emissions. Building on the existing Frisbee tool, the ENOUGH tool expands its scope to include a broader range of food processing operations, renewable energy integration and detailed transport emission modules. Key improvements include an updated computational core for refrigeration systems and an expanded database of food products.

The tool was applied in a series of case studies to evaluate the environmental impact of various operational practices and technologies within specific food supply chains. These simulations were complemented by an in-depth investigation into energy integration and waste heat recovery potential, using exergy analysis to identify inefficiencies and optimise energy use.

Simulation results showed strong alignment with established benchmark studies, enabling robust scenario comparisons and accurate identification of opportunities for environmental performance improvements.

Importantly, the ENOUGH tool is free to use and will remain available beyond the end of the project. It will continue to be maintained and developed by INRAE, ensuring long-term accessibility and relevance for industry, researchers and policy makers.

Key findings from the case studies include:

- **Packaging optimisation**: Switching from traditional non-recycled expanded polystyrene (PS) to recycled or reused materials can reduce supply chain emissions by 10%. Using advanced packaging technologies can deliver a further 61% reduction, resulting in total savings of up to 72% compared to conventional packaging and technologies.
- **Geographic sourcing impact**: Locally grown products, such as apples, have a significantly lower environmental footprint than imported alternatives, primarily due to reduced transport emissions. By combining local sourcing with recycled packaging, optimised refrigeration and

low-emission transport (e.g. biomethane-fuelled trucks and electric vehicles), emissions in the apple supply chain can be reduced by up to 90%.

- **Transport modality assessment**: Switching from air to sea freight for frozen salmon, even with a threefold increase in transport distance, results in a 90% reduction in transport-related emissions. The freezing and low-temperature transport processes contribute minimally to overall emissions, and sensory evaluations show negligible impact on product quality.
- **Energy integration and waste heat recovery**: Exergy analysis identified waste heat as a valuable but underutilised energy source across the food supply chain. Technologies for recovery include passive systems (e.g. regenerative heat exchangers, thermosiphons, heat pipes, thermal storage) and active systems (e.g. high-temperature heat pumps, cogeneration, absorption/adsorption chillers). Anaerobic digestion of organic waste was also recognised as a key opportunity for recovering chemical energy.
- **Tool attributes**: The ENOUGH tool differs from traditional Life Cycle Assessment (LCA) tools by offering dynamic modelling of cold chain logistics. It provides real-time data on product quality degradation, energy consumption and emissions. Unlike static LCA approaches, it enables step-by-step evaluation and targeted recommendations for reducing carbon footprints. The inclusion of product quality as an assessment factor, based on time–temperature relationships, is a unique feature. Designed to be user-friendly, the tool allows non-experts to model scenarios and supports broader stakeholder engagement.

3.4.1 Recommendations for industry

- Implement circular economy principles for packaging by prioritising reusable and recyclable materials to significantly reduce supply chain emissions.
- Optimise supply chain sourcing by favouring local procurement of raw materials and finished products where geographically and economically feasible, thereby reducing emissions from long-distance transport.
- Re-evaluate transportation logistics by systematically assessing transport modes and prioritising lower-emission options, such as sea freight over air transport, even when distances are greater.
- Integrate advanced low-emission technologies, including improved refrigeration systems, solar thermal and photovoltaic integration for cold storage, natural refrigerants, and bio-derived or electric fuels for transport fleets.
- Exploit waste heat recovery opportunities by conducting energy audits to identify waste heat streams and implementing passive and active recovery technologies to improve energy efficiency and reduce operational costs.
- Consider thermal energy storage (TES) to bridge the gap between waste heat availability and demand, enhancing system efficiency and maximising recovery potential.
- Leverage computational tools for decision support, such as the ENOUGH tool, to evaluate environmental performance, quantify the impact of interventions and identify optimal strategies for emissions reduction tailored to specific operational contexts.

3.4.2 Recommendations for policy makers

- Establish incentive systems for sustainable practices, including grants, tax credits and subsidies to support the adoption of sustainable packaging, local sourcing and low-emission technologies in the food sector.
- Promote investment in energy recovery infrastructure by creating policies that facilitate capital investment in waste heat recovery and energy integration technologies across the food supply chain.

- Allocate funding for research and development (R&D) to advance sustainable food supply chain technologies and improve analytical tools such as the ENOUGH tool.
- Facilitate technology transfer and dissemination by supporting initiatives that promote broad access to decision-support platforms, enabling adoption of sustainable practices even among non-expert stakeholders.

3.4.3 Recommendations for society

- Prioritise local and seasonal food consumption to reduce the environmental impact of long-distance transport and support regional food systems.
- Support environmentally responsible businesses by choosing companies that demonstrate commitment to sustainability through practices such as recycled packaging, efficient logistics and low-emission technologies.
- Increase awareness of food supply chain impacts, including the environmental consequences of sourcing and transport choices, particularly high-carbon methods like air freight.
- Minimise food waste, recognising that reducing waste at the consumer level contributes significantly to lowering emissions across the entire food supply chain.

3.4.4 Key publications

- Leducq, D., Evans, J., Verboven, P., & Alvarez, G. (2023, August 21–25). An innovative tool to evaluate and optimize GHG emissions in the food supply. In Proceedings of the 26th IIR International Congress of Refrigeration, Paris, France. International Institute of Refrigeration. https://doi.org/10.18462/iir.icr.2023.0730

3.5 WP5: Smart data systems

WP5 developed the Smart Data Systems (SDS), a framework designed to support the long-term use and impact of the ENOUGH project results. The SDS framework integrates paradigms, technologies, and tools into a virtual backbone (the SDS Infrastructure) of services and a holistic ecosystem of runtime components, enabling ENOUGH stakeholders to interoperate in a unified and co-creative way, with sustainability at its core and aligned with the emerging vision of Enterprise 5.0.

Its central application is a digital platform that generates digital twins of supply chain entities and manages their life cycle. The platform integrates tools, applications, and business models to help food supply chain actors enhance sustainability through collaborative, data-driven decision-making. Each supply chain entity is created through a dedicated workflow that combines human-driven and automated operations. The first users are participants in a supply chain who wish to be qualified within the SDS framework and business model. At the outset, these actors are contacted, their specifications and requirements are collected, and they are then provided with interfaces and connectors to operate within the digital supply chain entity. From that point onward, they remain actively involved in the collective life cycle of the supply chain entity.

The digital twins of supply chain entities produced by the SDS platform can use and integrate blockchain-based applications for secure and transparent transactions, and tools for distributed decision-making using, for example, mixed reality and holonic management methods. These innovations enable more inclusive, collaborative and efficient management of food supply chains.

Four business use cases were demonstrated for the SDS framework, including life cycle management of supply chain entities, buying and selling applications in the SDS Marketplace, and introducing new innovations. On each of these use case the SDS platform instantiates applications that allow stakeholders to connect, share data and adopt sustainable virtuous practices more easily.

Importantly, WP5 shows how digital transformation can support the goals of Industry 5.0 by promoting openness, participation and innovation in food systems. It also opens new research opportunities in areas such as privacy, democratic data governance and blockchain-based sustainability incentives.

3.5.1 Recommendations for industry

The lessons learnt that can be transferred to industrial players are:

- To head for simplicity and collaboration. The food supply chain is a complex playground, thus keeping things simple helps on overall quality. Moreover, try to address the complexity through enhanced collaboration along the supply chain.
- To promote and support sustainability. By never forgetting that being into the Industry 5.0 framework means that the human is increasingly at the center of everything, and that all the dimensions of sustainability must be enforced at once.
- To consider adopting technologies coming from the continuously evolving framework of the Blockchain. It is a key component and opportunity for the digital transformation and for the sustainable introduction and control of digital technologies.
- To think systemically and holistically. Apply systems engineering and consider the whole and parts of a system as a connected entity. Apply system thinking in the assessment of performances.

3.5.2 Recommendations for policy makers

Policy makers should pay attention to:

- Incentivizing digital transformation of food supply chain. In particular to be inclusive to SMEs and to create law devices and norms to lower market barriers and costs of the digital transformation.
- Supporting technology transfer in sustainability. Provide incentives to exploitation and dissemination of ENOUGH (or similar projects). Provide easy follow ups to initiatives like the SDS Framework to incentivize such kind of virtuous (in our opinion) approaches.
- Increase systemic thinking. Although policy makers have started already with many initiatives to foster systemic thinking, they should provide more strength and practice towards this idea. Push more on interdisciplinary initiatives of technology transfer.

3.5.3 Recommendations for society

Major recommendations to society can be:

- Be responsible as consumers.
- Search and support sustainability in products.
- Do not worship digital technologies but help in shaping them as prosumers.
- Promote technologies acting for the social good.

3.5.4 Key publications

- Pirani, M., Cucchiarelli, A., Naeem, T., & Spalazzi, L. (2025). A Blockchain-Driven Cyber-Systemic Approach to Hybrid Reality. Systems, 13(4), 294.

- Pirani, M., Cucchiarelli, A., Naeem, T., & Spalazzi, L. (2025, May). Verifiable Actor Model Systems Through Relational-Model Multi-Agent System and Zero-Knowledge Proofs. In 2025 IEEE 8th International Conference on Industrial Cyber-Physical Systems (ICPS) (pp. 01-06). IEEE.
- Pirani, M., Bonifazi, G., Cucchiarelli, a., Naeem, T., & Spalazzi, L. (2025, in press). Holonic Oracle Constructivism in Cyber-Physical Systems. In 2025 IEEE International Conference on Systems, Man, and Cybernetics (SMC). IEEE.
- Pirani, M., Carbonari, A., Cucchiarelli, A., Giretti, A., & Spalazzi, L. (2024). The Meta Holonic Management Tree: review, steps, and roadmap to industrial Cybernetics 5.0. Journal of Intelligent Manufacturing, 1-42.
- Pirani, M., Cucchiarelli, A., & Spalazzi, L. (2024, November). A Role of RMAS, Blockchain, and Zero-Knowledge Proof in Sustainable Supply Chains. In IECON 2024-50th Annual Conference of the IEEE Industrial Electronics Society (pp. 1-4). IEEE.
- Raikov, A., Giretti, A., Pirani, M., Spalazzi, L., & Guo, M. (2024). Accelerating human–computer interaction through convergent conditions for LLM explanation. Frontiers in Artificial Intelligence, 7, 1406773.
- Pirani, M., Cacopardo, A., Cucchiarelli, A., & Spalazzi, L. (2023, September). A Soulbound Token-based Reputation System in Sustainable Supply Chains. In EWSN (pp. 363-368).
- Spegni, F., Fratini, L., Pirani, M., & Spalazzi, L. (2023, March). ChoEn: A smart contract based choreography enforcer. In 2023 IEEE international conference on pervasive computing and communications workshops and other affiliated events (PERCOM workshops) (pp. 86-91). IEEE.

3.6 WP6: Demonstrations of best technologies in key products and cross sectors

WP6 has successfully concluded with 21 demonstrators finalised, each delivering tangible results. These outcomes have been systematically analysed, with key messages tailored to relevant stakeholders across sectors and products. Business plans have been developed and exploited for three selected demonstrators, while technologies and best practices have been actively disseminated. In addition, further development opportunities and follow-up activities have been identified, ensuring continuity beyond the project's scope.

Core messages from WP6 include:

- The future food chain can be fully supported by 100% natural refrigerant-based technologies (D2, D3, D4, D5, D7, D8, D10, D11, D12, D14, D15, D17, D18, D19, D20).
- Flow integration, energy storage, heat recovery, waste heat utilisation, and grid interaction are essential for decarbonisation (D2, D3, D8, D9, D11, D14, D16, D18).
- Electrification is viable for industrial heating and transport applications (D2, D3, D7, D8, D14).
- Innovative storage and processing methods can significantly reduce food waste at both professional and domestic levels (D4, D5, D12, D15, D17).
- Advanced control systems enhance emission reduction and improve trustability across the food chain (D1, D21).

Dissemination has been robust, with results shared through social media (videos, posts), conferences, workshops, and stakeholder meetings. The ENOUGH project has shown that substantial emissions reductions, up to 50%, are achievable using existing technologies. The success of 21 real-world demonstrations across Europe confirms that these solutions are both feasible and scalable, offering a clear path to decarbonising the food supply chain. The highest technology readiness level achieved is TRL 9, indicating full market readiness.

Examples include:

- Dairy sites in Austria and Norway, which achieved significant energy savings and CO_2 reductions through innovative heating and cooling systems.
- The transport demonstrators in Italy, which validated the use of natural refrigerants and electric-powered refrigerated transport.
- Other technologies demonstrated include advanced freezing methods (brine, blast, CO_2 plate freezing), energy-efficient fruit storage using dynamic controlled atmospheres (DCA), sustainable packaging, optimised retail technologies (heat reclaim, thermal storage, demand-side response, evaporator overfeeding, adoption of advanced components like pressure exchangers), and domestic innovations such as freeze dryers and efficient refrigerators.

3.6.1 Recommendations for industry

- Heating and processing
    - Adopt absorption-compression heat pumps for processes requiring hot water or steam (e.g. sterilisation, drying, cooking, cleaning), especially in meat, fish, and dairy sectors. This technology is also applicable in chemical and pharmaceutical industries.
    - Analyse thermal energy flows to optimise heating and cooling in dairies. Focus on system boundaries, temperature levels, and interdependencies.
    - Use existing production data and control systems (e.g. SCADA) for energy analysis. If additional measurements are needed, define scope, equipment, and data management clearly.
- Freezing and chilling
    - Implement advanced freezing systems (e.g. flooded evaporators, heat recovery) using natural refrigerants to reduce energy use and environmental impact.
    - Select freezing methods based on product type and processing volume.
    - Superchilling is a promising alternative for large-scale food storage and distribution, with relevance across the entire supply chain.
- Storage and preservation
    - Dynamic Controlled Atmosphere (DCA) is recommended over conventional ULO for long-term fruit and vegetable storage, offering better quality preservation and up to 15% energy savings.
    - Scale down energy-efficient freeze-driers for broader application, including domestic use.
- Packaging
    - Recycled PET and paper-based punnets are viable alternatives to conventional plastic packaging.
    - PLA-based biodegradable packaging has potential but requires dedicated waste management and improved material stability.
- Transport
    - Natural refrigerant-based transport units are viable and nearing market readiness (TRL 7–8). Demo 7's CO_2 unit architecture may also suit stationary refrigeration.
    - Collaborate across academia and industry to develop components optimised for transport: lightweight, compact, and efficient.
- Retail and cold storage
    - Retail refrigeration and cold stores can fully rely on natural refrigerant systems, which are efficient, reliable, and cost-effective.

  - Consider integrating thermal energy storage (TES) into supermarket heating systems to pre-heat ventilation air or support heat pumps.
- Digitalisation and SME inclusion
  - Lightweight interoperability (Demo 1) via SDS technology lowers barriers for SMEs to join complex supply chains, enabling support and continuous improvement through shared systems and decision-making tools.

3.6.2 Recommendations for policy makers

- Introduce financial incentives and subsidies to accelerate adoption of absorption-compression heat pumps in food industry processes.
- Support superchilling technology through targeted funding, R&D programmes, green public procurement, and industry training.
- Promote the phase-out of synthetic refrigerants in freezing plants and refrigerated transport; CO_2 offers a safe and scalable alternative.
- Incentivise energy monitoring and management systems in dairy production to improve efficiency and reduce emissions.
- Encourage sustainable value creation in food supply chains by supporting interoperable digital tools that lower entry barriers for SMEs.
- Promote energy-efficient technologies like DCA for long-term fruit and vegetable storage to reduce food losses.
- Raise awareness of packaging's role in reducing food waste and support the development of waste management systems for biodegradable materials.
- Strengthen F-Gas Regulation and related policies to enable the transition to natural refrigerants in transport refrigeration.
- Update transport refrigeration performance standards (e.g. ATP – UNECE) to prioritise energy efficiency and support innovation in logistics.
- Ensure new refrigeration installations use only natural working fluids to support clean technology investment and operational savings.
- Highlight the potential of freeze-drying and digital tools for mapping food loss and waste as part of food waste reduction strategies.
- Facilitate collaboration between academia and industry to develop lightweight, compact, and efficient components for transport refrigeration.
- Support continuous improvement of small-scale refrigeration cycles using natural refrigerants, advanced components, and control strategies.

3.6.3 Recommendations for society

- Support the transition away from fossil fuels by embracing cleaner, more efficient industrial heating technologies that reduce greenhouse gas emissions and improve food safety.
- Adopt superchilling technologies to reduce food waste, extend shelf life, and enhance food safety, while lowering energy consumption compared to conventional freezing.
- Choose energy-efficient freezing methods (e.g. brine) to reduce energy use and ease pressure on energy supply systems.
- Recognise the environmental benefits of frozen fish and meat products when processed using sustainable systems, contributing to reduced food waste and emissions.
- Increase public awareness of the energy and environmental footprint of dairy products to drive demand for cleaner production methods.
- Promote privacy-preserving digital tools (e.g. Demo 1) that support ethical and sustainable food supply chains, balancing collective and individual decision-making.

- Prefer DCA storage for organic fruit and vegetables, as it avoids chemical treatments and supports year-round availability of local produce while reducing emissions from imports.
- Choose recycled PET packaging for fruit and vegetables to support circular economy practices.
- Understand the importance of a dedicated cold chain for perishable foods to maintain quality and reduce spoilage.
- Encourage social acceptance of natural refrigerants in transport applications, highlighting their safety and reliability.
- Support urban well-being by adopting technologies that comply with Zero-Emissions Zones and Quiet Areas, such as TES-based last-mile delivery systems.
- Recognise and promote existing sustainable technologies for food storage and retail to enable widespread adoption.
- Consider alternative consumer technologies (e.g. freeze-drying) that extend shelf life and reduce energy consumption.

3.6.4 Key publications

There have been many publications from this work package, published both in journals and conference proceedings. The complete list of publications (updated to 30.07.2025) can be found in public deliverables D6.6-D6.12 (available from ENOUGH website). Here is a selection:

- Ren, S., Ahrens, M.U., Hafner, A. and Widell, K.N., 2022. Performance evaluation of high-temperature heat pump systems for hot water and steam generation in food processing. 15th IIR Gustav Lorentzen Conference on Natural Refrigerants – GL2022 Proceedings, Trondheim, Norway, 13–15 June. International Institute of Refrigeration.
- Selvnes, H., Jenssen, S., Sevault, A.G.E., Widell, K.N., Ahrens, M.U., Ren, S. and Hafner, A., 2022. Integrated CO_2 refrigeration and heat pump systems for dairies. 15th IIR Gustav Lorentzen Conference on Natural Refrigerants – GL2022 Proceedings, Trondheim, Norway, 13–15 June. International Institute of Refrigeration. https://doi.org/10.18462/iir.icr.2023.0435
- Bless, M., 2023. Model-based investigation of upgraded thermal energy system designs of the organic dairy in Røros – with PCM-storage integration and experimental pressure drop analysis of pillow plates. MSc thesis, NTNU. Available at: https://hdl.handle.net/11250/3094653
- Verdnik, M.; Wagner, P.; Rieberer, R. (2023): Operating Strategies of an Industrial R717 Heat Pump Recovering Waste Heat of a Chiller. In: Proc. 26th IIR International Congress of Refrigeration (ICR 2023). Paper 696. Paris, France, August 24-30. International Institute of Refrigeration
- Yedmel, Maria Aurely, R. Hunlede, Stéphanie O. L. Lacour, Graciela Alvarez, Anthony Delahaye, et Denis Leducq. A Novel Approach to Integrate Cold Energy Storage in a Vapour Compression Cycle. 26th IIR International Congress of Refrigeration (ICR 2023). https://doi.org/10.18462/iir.icr.2023.0467
- Improvement of domestic-scale freeze-dryer affordability by implementing vacuum-freezing technology, volumetric heating method and natural-based working fluid, EFFoST International Conference, 6-8 November 2023, Valencia, Spain.
- Fabris, F., Fabrizio, M., Marinetti, S., Rossetti, A. and Minetto, S., 2023. Comparison of the environmental impact of HFC and natural refrigerant transport refrigeration units from a life-cycle perspective. 10th IIR Conference on Ammonia and CO_2 Refrigeration Technologies, Ohrid, North Macedonia, 27–29 April. International Institute of Refrigeration. https://doi.org/10.18462/iir.nh3-co2.2023.0033
- Ren, S., Ahrens, M.U., Hamid, K., Tolstorebrov, I., Hafner, A., Eikevik, T.M. and Widell, K.N., 2023. Performance modelling of an ammonia-water absorption-compression heat pump for

steam generation in food processing. 10th IIR Conference on Ammonia and CO_2 Refrigeration Technologies, Ohrid, North Macedonia, 27–29 April. International Institute of Refrigeration.

- Ren, S., Ahrens, M.U., Hamid, K., Tolstorebrov, I., Hafner, A., Eikevik, T.M. and Widell, K.N., 2023. Numerical investigation of an ammonia-water absorption-compression high-temperature heat pump for hot water and steam production in food processing. Proceedings of the 26th IIR International Congress of Refrigeration, Paris, France, 21–25 August. Vol. 4. International Institute of Refrigeration.
- Verlinden, B.E., Bessemans, N., Verboven, P., Nicolai, B.M. (2023). Saving energy using RQ-based dynamic controlled atmosphere storage of blueberry fruit. In: *26TH IIR INTERNATIONAL CONGRESS OF REFRIGERATION, VOL 3*. Presented at the 26th International Congress of Refrigeration (IIR), FRANCE, Paris, 21 Aug 2023. DOI: 10.18462/iir. 10.18462/iir.icr.2023.0954
- Selvnes, H., Jenssen, S., Sevault, A.G.E., Bengsch, J., Widell, K.N., Ahrens, M.U., Ren, S. and Hafner, A., 2023. Integrated CO_2 refrigeration and heat pump system for a dairy plant: Energy analysis and potential for cold thermal energy storage. Proceedings of the 26th IIR International Congress of Refrigeration, Paris, France, 21–25 August. Vol. 2. International Institute of Refrigeration. ISBN 978-2-36215-056-2, pp. 1546–1555.
- Minetto, S., Fabris, F., Marinetti, S., Rossetti, A. (2023). A review on present and forthcoming opportunities with natural working fluids in transport refrigeration. International Journal of Refrigeration, 152(April), 343–355. https://doi.org/10.1016/j.ijrefrig.2023.04.015
- Bengsch, J., Köster, L., Svendsen, E.S., Selvnes, H. and Widell, K.N., 2024. Sizing and optimization of a cold thermal energy storage (CTES) for a dairy: A case study. 8th IIR International Conference on Sustainability and the Cold Chain, Tokyo, Japan, 9–11 June. http://dx.doi.org/10.18462/iir.iccc2024.1060
- Svendsen, E.S., Indergård, E., Bengsch, J., Widell, K.N., Köster, L. and Nordtvedt, T.S., 2024. Improving energy efficiency in seafood freezing with brine technology. 8th IIR International Conference on Sustainability and the Cold Chain, Tokyo, Japan, 9–11 June. https://doi.org/10.18462/iir.iccc2024.1029
- Fabris, F., Minetto, S., Marinetti, S. and Rossetti, A., 2024. Numerical characterization of a propane–CO_2 refrigeration system developed for TES last-mile delivery. 8th IIR International Conference on Sustainability and the Cold Chain, Tokyo, Japan, 9–11 June. https://doi.org/10.5281/zenodo.13985656
- Ren, S., Hafner, A., Rekstad, I.H., Widell, K.N., Svendsen, E.S. and Nordtvedt, T.S., 2024. Design and freezing performance study of a CO_2 plate freezer at –50 °C evaporation temperature. Proceedings of the 16th IIR Gustav Lorentzen Conference on Natural Refrigerants – GL2024, 2024. International Institute of Refrigeration. https://doi.org/10.18462/iir.gl2024.1198
- Pirani, M., Cucchiarelli, A., & Spalazzi, L. (2024, November). A Role of RMAS, Blockchain, and Zero-Knowledge Proof in Sustainable Supply Chains. In *IECON 2024-50th Annual Conference of the IEEE Industrial Electronics Society* (pp. 1-4). IEEE
- Fabris, F., Minetto, S., Marinetti, S. and Rossetti, A., 2025. Numerical evaluation of a propane cooling unit for transportable insulated boxes equipped with eutectic tube TES. 1st IIR International Conference on Refrigeration Adapting to Rising Temperatures, Manchester, UK, 10–13 August. International Institute of Refrigeration. https://doi.org/10.18462/iir.adaptation.2025.166
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- Trabucchi, S., Farkas, D., Tarjan, G., Nemeth, L., Szabo, T., Orlandi, M., Mazzola, D. (2025) CO2 pressure exchanger technology in commercial refrigeration: a new case study towards technological maturity. DOI:10.18462/iir.adaptation.2024.1163.

3.7 WP7: Policy, strategy, advice to achieve targets

The combined findings from research, modelling, and stakeholder engagement across the WP7 activities reveal that decarbonising the EU food system, particularly its cold chain components, require a multi-level approach that integrates technological, policy, and behavioural strategies. The technological roadmaps developed under WP2 provide a concrete vision for innovation across the food cold chain, identifying key priority areas for reducing emissions in transport logistics, cold storage infrastructure, and household-level food preservation. The WP7's assessment shows significant policy gaps between current regulatory frameworks and the decarbonisation potential of these technologies. There is a lack of alignment between climate, energy, and food policies, which hinders coordinated action across the food supply chain. For example, while there are isolated efforts to reduce energy consumption in food logistics or promote sustainable refrigeration systems, these are rarely integrated into a broader, unified policy framework that supports a low-carbon food system from “farm to fork.”

Furthermore, existing policies do not sufficiently account for future food system needs outlined in strategic documents such as the European Commission’s *FOOD 2030 Research and Innovation Pathways for Action 2.0*. This could lead to slow down innovation adoption and missing opportunities for emissions reductions. The WP7’s work highlights the importance of aligning policy tools with technological readiness levels, particularly by supporting emerging technologies in the demonstration and market entry phases.

At the societal level, consumer behaviour remains a pivotal but underleveraged driver of food system transformation. Survey and estimation results indicate that sustainability-oriented food choices are strongly influenced by socioeconomic factors. Consumers with higher levels of education and income are significantly more likely to prioritize sustainability elements when purchasing food products. Moreover, individuals with elevated socioeconomic and educational status are more likely to be better informed about organic food and short supply chains. However, sustainability awareness and willingness to pay for green products remain uneven, with many consumers still misinformed or disengaged, especially when it comes to understanding complex eco-labels or carbon footprint metrics.

Regional disparities also emerge. In North-Western EU countries, consumer engagement in sustainability initiatives is typically more robust, often supported by civil society and NGOs. In contrast, South-Eastern EU countries rely more heavily on top-down EU initiatives, reflecting lower levels of civic participation. These regional differences underscore the need for place-based policy design and local empowerment strategies.

In terms of enabling change, WP7 identifies three key strategic pathways:

1. Developing a coordinated policy framework that bridges existing gaps across the food, energy, and climate sectors, supporting emissions reduction at every stage of the food system, especially in more upstream stages such as distribution and consumption.
2. Promoting consumer behaviour change through simplified and harmonized eco-labelling schemes, large-scale awareness campaigns, and long-term educational investments.

3. Supporting workforce development by funding training programs for food system actors, including drivers, cold storage technicians, and appliance installers, who are central to operationalising energy-efficient technologies.

Ultimately, the transition to a sustainable and low-carbon food system will depend not only on technological readiness and political will but also on engaging society through equitable, informed, and participatory processes. Behavioural change must be supported by clear information, affordable green choices, and systemic policy interventions that reflect the complexity of the food system. Without these coordinated efforts, the goals of the EU's Farm to Fork Strategy risk being confined to niche markets and higher-income groups, leaving behind broader segments of the population.

3.7.1 Recommendations for industry

- Adopt proving, low-emission technologies such as systems with natural refrigerants, energy-efficient insulation, induction cooktops and inverter-driven appliances.
- Prioritise solutions with high emissions reduction potential and proven technological readiness (TRL 8–9), particularly in refrigerated transport, cold storage and food preparation.
- Develop company or sector-specific roadmaps that include energy audits, GHG baselining, retrofitting plans and workforce training to align with EU climate targets.
- Build partnerships with logistics providers, cold storage operators and technology suppliers to enable integrated decarbonisation efforts.
- Invest jointly in shared infrastructure and digital tools (e.g. performance tracking and IoT systems) to reduce costs and improve efficiency.
- Establish internal monitoring systems for fuel use, refrigerant leakage and energy consumption to support transparency and prepare for future ESG regulations and green finance opportunities.

3.7.2 Recommendations for policy makers

- Enforce minimum energy efficiency standards for transport refrigeration units, cold storage systems and domestic kitchen appliances, supported by inspections, penalties and performance audits.
- Provide targeted financial support, including grants, concessional loans and fiscal incentives (e.g. tax credits and VAT reductions), especially for SMEs and low-income households.
- Increase EU funding for the deployment and scaling of clean technologies in the food industry, in line with Food 2030 and Horizon Europe priorities.
- Develop a coordinated policy framework that aligns climate, energy and food policies, embedding emissions reduction targets across the entire food supply chain. Especial attention is to be paid to downstream food supply chain stages.
- Launch public awareness campaigns to promote energy-saving practices and sustainable food choices.
- Simplify and strengthen eco-labelling schemes to help consumers make informed decisions and stimulate demand for low-carbon products.
- Fund targeted training programmes for key roles in the food system, including drivers, cold storage technicians, appliance installers and food industry operators.

3.7.3 Recommendations for society

- Make informed food choices by recognising the environmental and health impacts of everyday actions, such as buying locally produced food, reducing waste and cooking efficiently.

- Engage in long-term learning through education programmes, community workshops and school-based initiatives to improve sustainability awareness across all regions and demographics.
- Participate in civil society initiatives such as food cooperatives, environmental campaigns and consumer associations to amplify public influence and drive collective action.
- Support policies that ensure green products are affordable and accessible to all, helping to avoid deepening inequalities in sustainable consumption.
- Endorse market regulations that reflect environmental priorities while protecting low-income consumers from disproportionate costs.

3.7.4 Key publications

- Moreira-Dantas, I. R., Martínez-Zarzoso, I., & Torres-Munguía, J. A. (2022). Sustainable Food Chains to Achieve SDG-12 in Europe: Perspectives from Multi-stakeholders Initiatives. https://doi.org/10.1007/978-3-030-91261-1_90-1
- Moreira-Dantas, I.R., Martínez-Zarzoso, I., Torres-Munguía, J. A., Jafarzadeh, S., Martin, M. P., and Thakur, M. (2022). Sustainable food value chains in the European Union: linking policies and multi-stakeholders' initiatives. Agri-Tech Econ. Sustain. Futures 19, 183–186.
- Moreira-Dantas, I. R., Martínez-Zarzoso, I., Fernandes de Araujo, M. L., Evans, J., Foster, A., Wang, X., & Pujol Martin, M. (2023). Multi-stakeholder initiatives and decarbonization in the European food supply chain. Frontiers in Sustainability, 4, 1231684. https://doi.org/10.3389/frsus.2023.1231684

4 PROJECT MANAGEMENT AND COLLABORATION

Managing a large European project like ENOUGH requires careful coordination, clear communication, and a shared commitment to common goals. With 30 partners across 12 countries, success depends not only on technical expertise but also on structured and regular collaboration. Throughout the project, consistent communication, transparent decision-making, and mutual trust have been key to maintaining momentum and ensuring that all partners remained aligned. The consortium's ability to adapt to changes and maintain strong working relationships has been central to both the scientific impact and the human connections formed during the project.

Consortium structure and partner roles

Although 30 partners is a large number to collaborate with, it was important to include a wide variety of organisations, including universities, research institutions, non-profit organisations, and industry.

Universities contributed academic research and involved students, who interacted across national borders, building networks that will benefit their future careers. These students also gained valuable insights from the project that they will carry into their professional lives. Research institutes played a similar role to universities but often had slightly different ties to industry and stakeholders, enhancing dissemination and practical impact.

Industry participation was essential in this innovation project. With support from academia and EC funding, companies were able to reduce the risk associated with product development. Their extensive networks also helped amplify the project's visibility.

Regional diversity and its impact

From the outset, it was important to include partners from across Europe (north, south, east, west, and central). This diversity provided valuable insights into regional differences and similarities. For example, electricity sources vary significantly between countries, affecting carbon footprint calculations. Similarly, the implementation of natural refrigerants differs across regions, allowing some countries or sectors to serve as guides for others.

Future projects should aim to include partners from different countries and regions, as well as industry stakeholders. While participation in EU projects can be challenging for smaller companies, especially those unfamiliar with such collaborations, their involvement is crucial. Interdisciplinary collaboration can also be demanding, but dedicated activities focused on fostering collaboration can help overcome these challenges.

Work package collaboration and integration

While many central participants knew each other beforehand, the project also fostered new and stronger relationships. Work packages (WPs) typically have clear objectives, but cross-WP collaboration is equally important, although it is more complex. Some activities require input from other WPs, which can lead to delays or differing perspectives. In ENOUGH, a shared understanding of the overall goals enabled effective collaboration. For future projects, it is recommended to establish clear guidelines for inter-WP collaboration, including when and how it should occur.

Coordination through meetings and advisory support

Regular meetings have been central to maintaining coordination and transparency within the ENOUGH consortium. Monthly Work Package Leader (WPL) meetings have provided a structured forum for discussing cross-cutting topics such as webinars, annual meetings and reporting. Each WPL has presented updates on completed, ongoing and planned activities, with all discussions documented in meeting minutes. These minutes are shared via Teams and serve as a foundation for the annual reports. Annual meetings have been held during the summer in various locations, hosted by different partners. These gatherings have included presentations of results, planning of future activities and open workshops with external participants. In addition to group meetings, the project management team has conducted one-to-one meetings with individual partners, allowing for tailored discussions and suggestions for improvement. The advisory council, composed of volunteers from industry, academia and supporting organisations, has provided valuable guidance and assurance, strengthening stakeholder confidence and supporting environmentally responsible outcomes.

Risk management and issue resolution

Over a four-year project, many things can change, making risk management and follow-up essential. All partners were regularly informed, although much of the follow-up was handled discreetly by the management team. When issues arose, the relevant partners were involved in finding solutions. For example, one partner went bankrupt, triggering a lengthy administrative process with the Commission. Nevertheless, the WP team managed the situation effectively, resulting in only minor delays without compromising deliverables.

Gender balance in the project

The ENOUGH project shows a mixed picture in terms of gender balance. Women make up 31% of researchers and 46% of non-research staff. Notably, 9 out of 11 work package leaders are women, reflecting strong female representation in leadership. While the refrigeration sector has traditionally been male-dominated, the project demonstrates progress and highlights the importance of continued efforts to support gender diversity, especially in research roles.

External collaboration and synergies

External collaboration was also vital. The consortium shared project information and received input from other initiatives, enhancing understanding and impact. We collaborated with national projects through joint workshops and participated in a food working group with “sister” projects funded under the same EC call. This led to joint policy briefs and shared conference booths.

Future projects should plan for collaboration from the outset. Activities should be embedded in the project description rather than added later, as this ensures they are prioritised.

Reflections on successful project management

Successful project management relies on dedicated individuals who understand how people collaborate effectively. It also requires an appreciation of individual differences, empathy, and respectful communication. Reaching out directly and kindly, without publicly highlighting mistakes, has been key to maintaining a positive and productive working environment.

5 DISSEMINATION AND EXTERNAL COMMUNICATION

Dissemination of the project's goals, results and impact has been a priority from the outset. Early in the project, a dedicated website was launched to serve as a central platform for sharing news, events, publications and other relevant updates. This ensured that information was accessible to both partners and external stakeholders.

SINTEF Ocean, as the project coordinator, led the dissemination activities for much of the project duration. Their involvement across all work packages made it easier to stay informed and coordinate communication efforts. Collaboration with other partners was also essential, particularly with international organisations whose core activities include outreach and stakeholder engagement.

Scientific dissemination has included publications in peer-reviewed journals and conference proceedings. Participation in conferences has increased the project's visibility, and in some cases, dedicated workshops were organised to present specific project outcomes.

To support broader communication, fact sheets were produced to summarise key findings in a concise format, with links to more detailed publications. These materials have helped make complex information more accessible to a wider audience, including policymakers, industry representatives and the general public.

More details and photos, including publications and presentations are available at the ENOUGH webpage enough-emissions.eu.

Recommendations

- Establishing a solid plan for communication and dissemination in the beginning of the project is key to ensure visibility, outreach and impact. Identifying your key audience, channels and formats builds an important foundation. The plan should be discussed by project partners regularly (e.g. during yearly meetings) to ensure all partners are aligned.
- The European Commission (EC) has developed dedicated communication channels with different aims depending on current project phase (start, implementation and development, closure). Identifying when, how and where to promote the project in EC channels can increase visibility and impact, as these channels have high reach and authority.
- Monitoring the communication and dissemination activities is important to keep track of where and how the project results have been promoted, and to plan future activities. It is also important for project reporting and to ensure that your KPIs (key performance indicators) are reached. In large projects like ENOUGH, easy and effectively monitoring of communication and dissemination activities can be challenging, so finding a good strategy is important.

6 CONCLUSIONS AND FUTURE RESEARCH OPPORTUNITIES

The food supply chain is one of the largest and most complex contributors to global greenhouse gas (GHG) emissions, responsible for approximately one third of the total. Its diversity, spanning SMEs and large enterprises, multiple subsectors, and varied regional and policy contexts, creates both challenges and opportunities for decarbonisation.

The ENOUGH project has shown that meaningful emission reductions are achievable. By combining technological innovation, digitalisation, and behavioural and policy insights, the project demonstrates clear pathways towards a more sustainable and resilient food system:

- Technologies at TRL 5–9, including natural refrigerant systems, thermal energy storage, high-efficiency heat pumps, and advanced freezing solutions, can deliver substantial reductions in energy use and emissions.
- Digital tools such as the SDS platform enable transparency, monitoring, and optimisation across supply chains, while also supporting SMEs with affordable solutions.
- Policy analysis reveals gaps between technological potential and current regulatory frameworks, highlighting the importance of coordinated support and incentives for adoption.
- Behavioural and dietary shifts, when combined with advanced technologies, could reduce emissions by over 30%, showing the vital role of consumer engagement and awareness.

The project confirms that there is no one-size-fits-all solution. Decarbonisation requires tailored strategies for each subsector, adapted to regional contexts, technological readiness, and societal acceptance. Demonstrations across Europe prove that solutions are already available and scalable, but their full impact depends on accelerated uptake, supported by aligned policies and investment.

In conclusion, ENOUGH provides evidence-based roadmaps and tools to bridge the gap between ambition and implementation. By fostering collaboration between industry, policymakers, researchers, and society, the project helps set the foundation for achieving near net-zero emissions in the food sector by 2050.

Future Research Opportunities

Future research should build on ENOUGH's achievements to address remaining knowledge gaps and accelerate the transition to a sustainable, low-emission food supply chain. Key areas include:

- Advanced Modelling and Data Tools
    - Expand and refine generic models (e.g., supermarkets, cold stores, transport) for use in multiple countries and contexts.
    - Integrate technologies and interactions in system-level energy and emissions models.
    - Enhance the ENOUGH tool by broadening databases, improving user interfaces, and validating predictions with diverse case studies.
    - Develop robust mathematical and transient simulation models to support industry decision-making.
- Technological Innovation and Integration
    - Optimise refrigeration, freezing, and heat pump systems (e.g., brine freezing, CO_2 plate freezers, superchilling) and explore applications in new sectors.
    - Advance integrated energy systems combining cold, heat, and power, including renewable sources and thermal storage.

    - Investigate AI- and blockchain-enabled controls for precise temperature management, energy optimisation, and transparency in supply chains.
    - Support academia–industry collaboration for the design of compact, efficient, and application-specific components.
- Sustainability Assessment and Techno-Economics
    - Expand assessments beyond GHGs to include water, land use, biodiversity, and life-cycle impacts.
    - Conduct techno-economic feasibility studies of emerging solutions in real industrial settings, with focus on SMEs.
    - Quantify system-level impacts of new business models and cross-sector integration strategies.
- Behaviour, Society, and Policy
    - Investigate socio-economic and cultural drivers of adoption for sustainable food practices and technologies.
    - Assess the effectiveness of eco-labelling schemes, incentives, taxes, and subsidies across EU regions.
    - Explore inclusivity of sustainable food transitions, ensuring access for all socio-economic groups.
    - Examine barriers and adoption challenges for SMEs, retailers, and consumers, and design strategies for a just transition.
- Cross-Sector and Regional Perspectives
    - Study coordination mechanisms to scale integrated energy solutions across the food chain.
    - Compare regional contexts within and beyond Europe to understand cultural norms, infrastructure, and policy impacts on decarbonisation.
    - Encourage global application of ENOUGH tools and methodologies, adapted to specific climatic and socio-economic conditions.

7 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588.

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Disclaimer: This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588.