ENOUGH

EUROPEAN FOOD CHAIN SUPPLY TO REDUCE GHG EMISSIONS BY 2050

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TABLE OF CONTENTS

Nomenclature 5
EXECUTIVE SUMMARY 5
1 Introduction 6
2 Overview 6
3 Food processing 8
3.1 Food processing road map 8
3.2 Technologies demonstrated in ENOUGH 9
3.2.1 Dairy 9
3.2.2 Freezing 10
4 Cold storage 11
4.1 Cold storage road map 11
5 Food transport 11
5.1 Food transport road map 11
5.2 Technologies demonstrated in ENOUGH 12
6 Retail 13
6.1 Retail road map 13
6.2 Technologies demonstrated in ENOUGH 14
7 Catering / food service 15
7.1 Food service road map 15
8 Domestic 15
8.1 Domestic road map 15
8.2 Technologies demonstrated in ENOUGH 16
9 Conclusions 17

LIST OF FIGURES

FIGURE 1. SEVEN MAIN RECOMMENDATIONS TO REDUCE CARBON IN THE FOOD PROCESSING INDUSTRY. 8

FIGURE 2. SIX MAIN RECOMMENDATIONS TO REDUCE CARBON IN THE COLD STORAGE SECTOR. 11

FIGURE 3. SIX MAIN RECOMMENDATIONS TO REDUCE CARBON IN FOOD TRANSPORT VEHICLES. 12

FIGURE 4. SIX MAIN RECOMMENDATIONS TO REDUCE CARBON IN SUPERMARKETS. 14

FIGURE 5. SEVEN MAIN RECOMMENDATIONS TO REDUCE CARBON IN FOOD SERVICE RESTAURANTS. 15

FIGURE 6. FOUR MAIN RECOMMENDATIONS TO REDUCE CARBON IN DOMESTIC HOME KITCHENS. 16

LIST OF TABLES

TABLE 1 OVERVIEW OF TECHNOLOGY ROADMAPS PRODUCED IN THE ENOUGH PROJECTS. ALL ROADMAPS ARE OPENLY AVAILABLE AT ENOUGH-EMISSIONS.EU. 6

TABLE 2 OVERVIEW OF THE ENOUGH DEMONSTRATORS, INCLUDING THE SECTOR AND/OR TECHNOLOGY THEY REPRESENT, AND THE DEDICATED REPORTS WHERE MORE INFORMATION IS AVAILABLE. 7

TABLE 3. MAIN RECOMMENDATIONS TO INDUSTRY, POLICY MAKERS AND SOCIETY BASED ON THE ENOUGH DEMONSTRATORS IN THE DAIRY SECTOR. 9

TABLE 4 MAIN RECOMMENDATIONS TO INDUSTRY, POLICY MAKERS AND SOCIETY BASED ON THE ENOUGH DEMONSTRATORS IN THE FISH SECTOR. 10

TABLE 5 MAIN RECOMMENDATIONS TO INDUSTRY, POLICY MAKERS AND SOCIETY BASED ON THE ENOUGH DEMONSTRATORS IN THE TRANSPORT SECTOR. 12

TABLE 6 MAIN RECOMMENDATIONS TO INDUSTRY, POLICY MAKERS AND SOCIETY BASED ON THE ENOUGH DEMONSTRATORS IN THE STORAGE AND RETAIL SECTOR. 14

TABLE 7 MAIN RECOMMENDATIONS TO INDUSTRY, POLICY MAKERS AND SOCIETY BASED ON THE ENOUGH DEMONSTRATORS IN THE DOMESTIC SECTOR. 16

Nomenclature

ACHP	Absorption-compression heat pump
ASHP	Air source heat pump
CTES	Centralised Cold Thermal Energy Storage
DCA	Dynamic controlled atmosphere
DSR	Demand side response
EEV	Electronic expansion valve
F-gas	Fluorinated gas
FLW	Food loss and waste
GHG	Greenhouse gas
GWP	Global warming potential
HFC	Hydrofluorcarbon
HTHP	High temperature heat pump
KPI	Key performance indicator
RES	Renewable energy source
RQ	Respiratory quotient
SOTA	State-of-the-art
TES	Thermal energy storage
TRL	Technology readiness levels
TRU	Transport refrigeration unit
TTA	Thermosiphon Thermal Accumulator

EXECUTIVE SUMMARY

The following report represents an overview of results arising from the ENOUGH project regarding technologies and operational practices that could reduce emissions and energy consumption in the food industry. Highlights from technological roadmaps for various stages of the food supply chain (food processing, storage, transport, retail, catering and domestic) are presented, as well as key technologies demonstrated through the 21 ENOUGH demonstrators across Europe.

The report also includes links to related reports and to the ENOUGH website, where more detailed information and full documentation are available.

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1 INTRODUCTION

The ENOUGH project tackles a significant source of greenhouse gas (GHG) emissions: the food supply chain. The project looks at several main food types in all steps of the post-harvest/slaughter food chain. To reduce emissions, there are several technologies and operational practices that can be implemented. Refrigeration systems (cooling and freezing) are major energy consumers and sources of emissions in the food chain, and improving these systems can drastically cut emissions. Examples are switching from synthetic refrigerants to natural refrigerants, improving insulation, increasing electrification through renewable energy, and phasing out fossil fuels.

In the ENOUGH project, tailored technological roadmaps for various stages of the food supply chain were generated (food processing, storage, transport, retail, catering and domestic), across six countries. These roadmaps prioritise practical, market-ready solutions with high technology readiness levels (TRLs). In parallel, ENOUGH has implemented 21 real-world demonstrators implemented technologies that could reduce emissions to prove that these solutions are not only feasible but scalable, offering a clear path to decarbonising the food supply chain.

This report summarises the main technologies explored by the ENOUGH project, to inform and encourage its implementation.

2 OVERVIEW

The tables below provide an overview of the roadmaps produced in the project (Table 1) as well as the 21 demonstrators in ENOUGH, including which sector and/or technology they represent and where more information on each initiative can be found (Table 2). All roadmaps are openly available on the ENOUGH webpage (enough-emissions.eu). Detailed information about each demonstrator (including e final reports on each demonstrator) are also available on the web site.

Table 1 Overview of technology roadmaps produced in the ENOUGH projects. All roadmaps are openly available at enough-emissions.eu.

Name	Description
D2.1 Road map structure document	Description of the specifications, structure and methodology for developing the road maps. All roadmaps contain a review of state-of-the-art and future technologies that can reduce emissions in the specific sector, and include modelling and predictions of possible savings.
D2.2 Food retail road map	95 technologies reviewed. 6 key recommendations.
D2.3 Food catering road map	60 technologies reviewed. 7 key recommendations.
D2.4 Cold storage road map	30 technologies reviewed. 6 key recommendations.
D2.5 Food transport road map	29 technologies reviewed. 6 key recommendations.
D2.6 Food storage in domestic homes road map	54 technologies reviewed. 4 key recommendations.
D2.7 Food processing road map	54 technologies reviewed. 7 key recommendations.

Table 2 Overview of the ENOUGH demonstrators, including the sector and/or technology they represent, and the dedicated reports where more information is available.

Demo	Name	Main product category and/or sector	Technology	Detailed report (available at enough-emissions.eu)
1	Holistic supply chain management and control	Dairy	Smart data	D6.8 Report on dairy demonstrators
2	Energy smart dairy	Dairy, processing	Energy flows and optimisation, high temperature heat pump (HTHP), Centralised Cold Thermal Energy Storage (CTES), natural refrigerants	D6.8 Report on dairy demonstrators
3	HTHP Dairy Austria	Dairy, processing	HTHP, natural refrigerants	D6.8 Report on dairy demonstrators
4	Thermal HTHP integration dairy	Dairy, processing	Thermal integration, HTHP	D6.8 Report on dairy demonstrators
5	RQ-based DCA storage	Fruit and vegetables, storage	Respiratory quotient (RQ) based dynamic controlled atmosphere (DCA)	D6.8 Report on fruit and vegetable demonstrators
6	Climate Neutral Packaging	Fruit and vegetables, packaging/storage	Alternative packaging	D6.8 Report on fruit and vegetable demonstrators
7	Fresh and green delivery	Transport	Natural refrigerants, renewable energy, electrification	D6.10 Report on transport demonstrators
8	TES Last mile delivery	Transport	Thermal energy storage (TES), insulation, natural refrigerants	D6.10 Report on transport demonstrators
9	DSR and TES	Retail	Refrigeration system, Demand side response (DSR)	D6.11 Report on storage and retail demonstrators
10	Future retail display	Retail	Refrigerated display cabinet	D6.11 Report on storage and retail demonstrators
11	Thermal storage unit for refrigeration cycle	Retail	Refrigeration system, refrigerated display cabinet, thermal energy storage, Thermosiphon Thermal Accumulator (TTA), Centralised Cold Thermal Energy Storage (CTES)	D6.11 Report on storage and retail demonstrators
12	Long-term food storage	Domestic	Freeze-drying	D6.12 Report on domestic demonstrators
13	Next generation refrigerator	Domestic	Natural refrigerants, insulation, Electronic expansion valves (EEVs)	D6.12 Report on domestic demonstrators
14	150°C steam production heat pump	Meat, processing	Natural refrigerants, Absorption-compression heat pump (ACHP)	D6.6 Report on meat demonstrators
15	Brine freezing of	Fish, processing	Freezing (brine)	D6.7 Report on fish

Demo	Name	Main product category and/or sector	Technology	Detailed report (available at enough-emissions.eu)
	fish			demonstrators
16	Refrigerated Store Heat Advanced Recovery	Cold store	Refrigeration system, heat recovery	D6.11 Report on storage and retail demonstrators
17	Superchilling	Meat, Domestic	Superchilling	D6.6 Report on meat demonstrators
18	Blast freezer	Fish, processing	Freezing (blast)	D6.7 Report on fish demonstrators
19	COP2PX	Retail	Refrigeration system, CO2 pressure exchanger	D6.11 Report on storage and retail demonstrators
20	CO2 plate freezer	Fish, processing	Freezing (plate)	D6.7 Report on fish demonstrators
21	FLW Norway	Domestic	Food loss and waste (FLW) tools	D6.12 Report on domestic demonstrators

3 FOOD PROCESSING

3.1 Food processing road map

The focus of this road map is on how the food processing sector can decarbonise and rapidly reach net zero. The road map presents technologies and strategies available for the food processing sector to reduce their carbon emissions. 54 different technologies/strategies that could be applied in processing companies to reduce carbon emissions and energy consumption were reviewed. The full road map is available at the ENOUGH website, and highlights are also converted into a factsheet (one-pager). From the work, this roadmap presents 7 main recommendations to reduce carbon the food processing industry.

Figure 1. Seven main recommendations to reduce carbon in the food processing industry.

3.2 Technologies demonstrated in ENOUGH

Several demonstrators within ENOUGH demonstrated technologies related to food processing. Some demonstrated technologies within the dairy sector, some within freezing technologies (applied in the fish sector), and some within the meat processing sector. Several of the demonstrated technologies are transferable to other sectors and food products even though they originally were applied for specific sector/products. The processing demonstrators within ENOUGH are found in several reports; D6.6 Report on meat demonstrators, D6.7 Report on fish demonstrators, and D6.8 Report on dairy demonstrators.

3.2.1 Dairy

In ENOUGH, three demonstrators explored technologies within the dairy sector. The table summarise the main recommendations drawn out from the dairy demonstrators. **The full report on domestic demonstrators of ENOUGH is available as D6.18 Report on dairy demonstrators, openly available at enough-emissions.eu.**

Table 3. Main recommendations to industry, policy makers and society based on the ENOUGH demonstrators in the dairy sector.

Recommendations to industry	The analysis of (thermal) energy flows is key to efficiently cover the heating and cooling demand of dairies. Emphasis should be put on the system boundaries, interdependencies and relevant temperature levels. For plants already in operation, production data can be a data source for this analysis. Attention should be paid regarding the availability of additional sensor data within control systems (e.g. SCADA) and possible data export. If additional measurement data is needed, clearly define the scope of the analysis and needed measurement equipment, including the management of gathered measurement data. Details such as sensor placement should be given particular attention.
Recommendations to policy makers	Support frameworks that incentivize energy monitoring and management systems in dairy production.
Recommendations to society	Public awareness of energy and environmental footprint of dairy products can drive demand for cleaner production methods.
Future research opportunities	The study of thermal energy flows in dairy processing provides valuable foundation for applied research on energy efficiency and decarbonisation. Research should aim to bridge theory and industrial practice by using real-world data and case studies. Collaboration with industry partners and transparency in data handling (cleaning, aggregation, interpolation etc.) is essential to ensure quality in analyses. Model-based analysis using transient simulations can be used to analyse the demands. Depending on the complexity of the energy supply system (which can be drastically increased in case of preceding retrofits), certain simplifications are necessary. Strong involvement of experts of the specific plant can help identify relevant aspects.

3.2.2 Freezing

Freezing is typically the most energy-intensive step in seafood processing, often accounting for the majority of electricity consumption, but it significantly extends shelf life. This enables products to be transported by sea rather than by air, which can substantially reduce greenhouse gas (GHG) emissions. Some freezing technologies are suitable only for specific product categories, while others are versatile and applicable across a wide range of food sectors. In ENOUGH, three different freezing technologies was demonstrated in the fish sector: **brine freezing, blast freezing, and plate freezing**. Each offers distinct advantages depending on the product type, processing scale, and operational context. It should be noted that these can also be effectively applied to other products beyond fish.

- Brine freezing enables rapid and uniform cooling. Brine freezing of unwrapped products is only suited for whole or gutted fish with skin. Filets will absorb salt and get slightly brown. Vacuum packed products like fish fillets, meat and other, are well suited for brine freezing.
- Blast-freezers provides flexibility and high throughput, making it ideal for a wide range of products. It is already used for various products like fish, meat, fruit, berries and bread.
- Horizontal plate-freezers are known for its high energy efficiency and compact design. They are especially effective for products packed and distributed in flat carton boxes, typically fish, shellfish, seaweed, frozen berries and juices and others.

Several of these systems utilised CO_2-based vapour compression cycles, capable of reaching evaporator temperatures as low as –50°C, which is particularly beneficial for rapid freezing and preserving product quality. Additionally, the condenser heat from these systems can be recovered and repurposed for other thermal needs within the facility, such as cleaning or space heating. This integrated approach not only improves overall energy efficiency but also supports the transition away from fossil fuels by enabling the use of renewable energy sources and surplus heat.

Table 4 summarise main recommendations drawn from the fish demonstrators. **The full report on fish demonstrators of ENOUGH is available as D6.18 Report on fish demonstrators, openly available at enough-emissions.eu.**

Table 4 Main recommendations to industry, policy makers and society based on the ENOUGH demonstrators in the fish sector.

Recommendations to industry	Implement advanced freezing systems to significantly lower energy consumption and reduce the environmental impact of frozen fish processing. Adopt natural refrigerants and SOTA system design, including flooded evaporators and heat recovery. Choose the most suitable freezing method according to your product and volumes.
Recommendations to policy makers	There is a real opportunity to eliminate synthetics in low temp freezing plants. Safety issues can be overcome by CO2.
Recommendations to society	Use of more efficient freezing methods like brine may significantly reduce energy consumption, de-stressing energy supply systems. Frozen fish and meat products can help in reducing food waste and save emissions (when processed with sustainable systems).
Future research opportunities	Brine freezing may be adopted for other application areas within fish sector, but also for meat products. Optimization of equipment design and concept development is required from academia. Explore and exploit operations around triple point. The impact of different packaging materials and methods on freezing time and final product quality warrants detailed study.

4 COLD STORAGE

4.1 Cold storage road map

The cold storage sector covers large and small cold stores where food is stored in a chilled or frozen state. Many larger warehouses and regional distribution centres are owned by international conglomerates. Even so, their design may be very different. On the other hand, many smaller cold stores exist at food processing outlets, in retail stores and catering outlets.

Within the ENOUGH project, a road map was created, questioning how the cold store sector can decarbonise and rapidly reach net zero. 30 different technologies/strategies that cold stores could apply to reduce carbon emissions and energy consumption were reviewed. The full road map is available on the ENOUGH website, and highlights are also converted into a factsheet (one-pager). From the work, this roadmap recommends 6 main opportunities to reduce carbon in food cold stores.

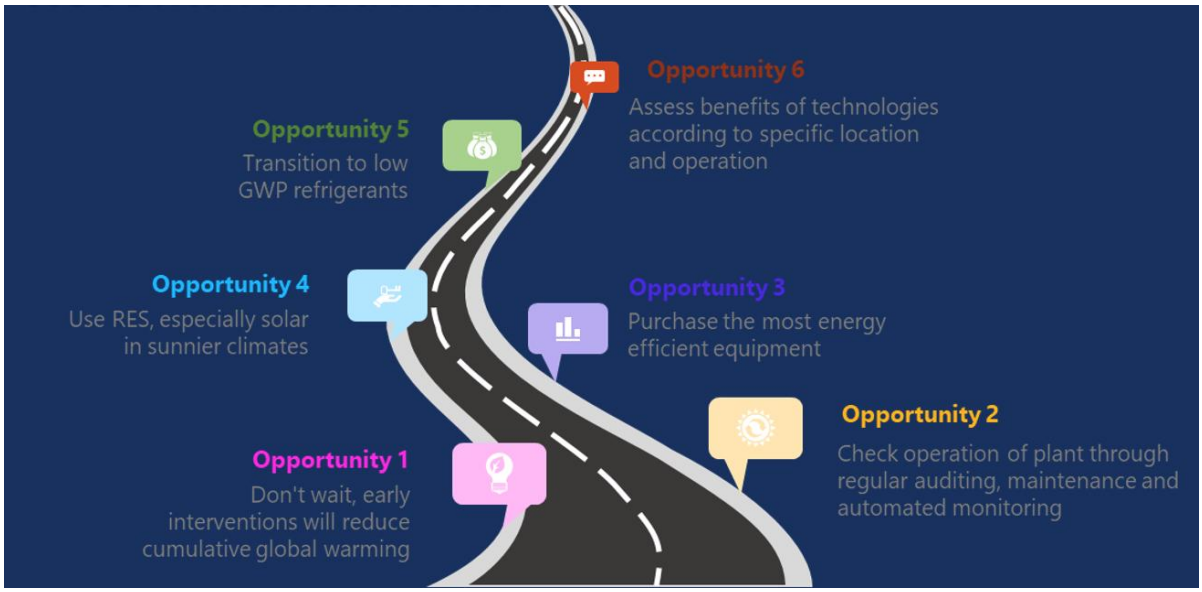

Figure 2. Six main recommendations to reduce carbon in the cold storage sector.

5 FOOD TRANSPORT

5.1 Food transport road map

The transport sector covers the transportation of food on the road, rail, rivers, sea and air. To contribute to the overall climate neutrality objective for 2050, the GHGs of the transport sector in the EU must be reduced by 90% compared to the baseline of 1990.

Within the ENOUGH project, a road map was created, questioning how the refrigerated food transport sector can decarbonise and rapidly reach net zero. The focus of the road map was on road transportation as this is the major method to transport food within Europe. It is claimed that in the EU 77% of food freight is by road. The road map presents quantified evidence on the levels of carbon that could be saved, the technologies and strategies that could be applied and looks forward to 2050 to predict whether a zero-carbon food transport sector is feasible.

29 different technologies/strategies that refrigerated transport vehicles could apply to reduce carbon emissions and energy consumption were reviewed. The full road map is available on the ENOUGH website, and highlights are also covered into a factsheet (one-pager). From the work, this roadmap presents 6 main recommendations to reduce carbon in food transport vehicles.

Figure 3. Six main recommendations to reduce carbon in food transport vehicles.

5.2 Technologies demonstrated in ENOUGH

In ENOUGH, two demonstrators explored technologies within the transport sector. The table summarise main recommendations drawn out from the transport demonstrators. **The full report on the ENOUGH transport demonstrators is available as D6.10 Report on transport demonstrators, openly available at enough-emissions.eu.**

Table 5 Main recommendations to industry, policy makers and society based on the ENOUGH demonstrators in the transport sector.

Recommendations to industry	Natural refrigerants-based transport units are viable, and they are in principle ready for final design and production stages (TRL 7-8). The refrigerated transport CO2 unit architecture developed for Demo 7 (Fresh & Green Delivery) could potentially be suitable even for stationary refrigeration units with medium/small size. Academia and industry should work together to develop specific components optimized for the sector, considering as key features low weight, high efficiency and compactness.
Recommendations to policy makers	The refrigerated transport sector is still dominated by synthetic refrigerants solutions. Fluorinated gases (F-Gas) Regulation and potential future policies should promote the phase-out of synthetic refrigerants in transport to allow development of natural refrigerants counterparts. Regulations setting the minimum performance requirements in transport refrigeration (for example, ATP – Unece) should promote uptake of innovative technical and logistics solutions and energy

	efficiency of refrigeration units should be prioritized in the transition towards electrical vehicles.
Recommendations to society	Natural refrigerants in transport applications can be safe and reliable. Their social acceptance should be therefore promoted. Demonstrated solutions are in line with the promotion of well-being in urban areas, by complying with Zero-Emissions Zones regulations. Demo 8 (TES Last-Mile Delivery) can also comply with Quiet Areas in city centres.
Future research opportunities	Academia and industry should work together to develop specific components optimized for the sector, considering as key features low weight, high efficiency and compactness. Given the unique features of naturals, academia should identify the best technical solutions, tailored on the specific transport application (last-mile, long-haul, etc.), climatic and socio-economic boundaries.

6 RETAIL

6.1 Retail road map

The retail sector has relatively high scope 1 and 2 emissions compared to other sectors of the food chain. Refrigeration is often the largest energy load in a supermarket. The energy consumption of supermarkets depends on business practices, store format, product mix, shopping activity and the equipment used for in-store food preparation, preservation, and display.

Within the ENOUGH project, a road map was created, questioning how the retail food sector can decarbonise and rapidly reach net zero. The road map presents quantified evidence on the levels of carbon that could be saved, the technologies and strategies that could be applied and looks forward to 2050 to predict whether a zero-carbon supermarket is feasible. 95 different technologies/strategies that retail stores could apply to reduce carbon emissions and energy consumption were reviewed. The full road map is available on the ENOUGH website, and highlights are also covered into a factsheet (one-pager). From the work, this roadmap recommends 6 major opportunities for supermarkets.

Figure 4. Six main recommendations to reduce carbon in supermarkets.

6.2 Technologies demonstrated in ENOUGH

Several demonstrators explored technologies within the storage and retail sector in the ENOUGH project. The table summarise main recommendations drawn from the storage and retail demonstrators. **The full report on the ENOUGH storage and retail demonstrators is available as D6.11 Report on storage and retail demonstrators, openly available at enough-emissions.eu.**

Table 6 Main recommendations to industry, policy makers and society based on the ENOUGH demonstrators in the storage and retail sector.

Recommendations to industry	Retail refrigeration and cold stores can rely on only natural systems, being available, reliable, efficient and cost-saving. Consider integration of supermarket store heating system with a thermal energy storage (TES) to either pre-heat ventilation air or provide heat source for a heat pump, also in existing systems.
Recommendations to policy makers	New installations should only apply natural working fluids, to help the asset owners investing in clean technology, enabling them to report sustainability and saving operational expenses.
Recommendations to society	Technologies for making storage and retail sustainable do exist and need societal recognition to be widespread adopted.
Future research opportunities	Academia and industry should continue to work together to investigate further improvements and thereby accelerate the phase out of hydrofluorcarbon (HFC) systems. Adoption of state-of-the-art (SOTA) components technologies (heat recovery, integration, increased evaporation by flooded evaporator, TES, etc) needs to be scientifically supported with multidisciplinary approach and documented. Further investigation of heat recovery from cold store evaporative condensers should be undertaken.

7 CATERING / FOOD SERVICE

7.1 Food service road map

The food service sector covers restaurants, cafes, pubs, bars, fast food outlets, and other establishments (such as schools, colleges, hospitals and other institutional facilities) that serve food and drinks to customers.

Within the ENOUGH project, a road map was created, questioning how the food service sector can decarbonise and rapidly reach net zero. 60 different technologies/strategies that food service outlets could apply to reduce carbon emissions and energy consumption were reviewed. The full road map is available on the ENOUGH website, and highlights are also covered into a factsheet (one-pager). From the work, this roadmap recommends 7 main recommendations to reduce carbon in food service restaurants.

Figure 5. Seven main recommendations to reduce carbon in food service restaurants.

8 DOMESTIC

8.1 Domestic road map

The domestic sector in Europe generates significant quantities of carbon emissions and so have a major role to play reducing emissions. Within the ENOUGH project, a road map was created, questioning how domestic food kitchens can decarbonise and rapidly reach net zero.

The road map presents cooling and heating technologies and strategies available for domestic kitchens to reduce their carbon emissions. This covers the emissions that they generate today and how emissions moving to 2050 could be reduced to ultimately assess how household kitchens could become zero carbon.

54 different technologies/strategies that could be applied in domestic kitchens to reduce carbon emissions and energy consumption were reviewed. The full road map is available on the ENOUGH

website, and highlights are also covered into a factsheet (one-pager). From the work, this roadmap presents 4 main recommendations to reduce carbon in domestic home kitchens.

Figure 6. Four main recommendations to reduce carbon in domestic home kitchens.

8.2 Technologies demonstrated in ENOUGH

In ENOUGH, three demonstrators explored technologies within the domestic sector. The table summarises the main recommendations drawn out from the domestic demonstrators. **The full report on domestic demonstrators of ENOUGH is available as D6.12 Report on domestic demonstrators, openly available at enough-emissions.eu.**

Table 7 Main recommendations to industry, policy makers and society based on the ENOUGH demonstrators in the domestic sector.

Recommendations to industry	The advanced small-scale refrigeration cycles based on the natural refrigerants should be continuously improved by application of the refrigerant blends, new components or control strategies. Further possibilities of scale-down energy-efficient freeze-driers should be heavily studied.
Recommendations to policy makers	The possibilities of the food waste limitations via alternative methods, i.e. freeze-drying and digital tool for mapping food loss and waste should be emphasised by policymakers.
Recommendations to society	Consumers should consider alternative methods that can provide longer shelf life and reduce energy consumption.
Future research opportunities	The robust mathematical models for the emerging cold-chain technologies should be developed by academia to support the industry's effort in the implementation of the new technologies and control strategies.

9 CONCLUSIONS

The technological roadmaps for various food chain stages (retail, catering, storage, transport, domestic, processing developed within the ENOUGH project demonstrates how significant emission reductions are achievable through technological and operational measures. There are many options available for carbon reduction, like electrification (move from fossil fuels), purchasing efficient equipment, minimising heat gains (e.g. infiltration, better insulation, operational efficiency, alternative practices/technologies), use of renewable energy, moving to natural refrigerants, use of heat pumps (low, plus high temperature), heat reclaim/exchange, auditing and maintenance.

The 21 real-world ENOUGH demonstrators proved that technological solutions are feasible, scalable and adaptable to different products and sectors. These solutions will need to be considered not only by industry actors, impact will also rely on the awareness and action among policy makers, consumers and research.

In conclusion, substantial emission reductions can be achieved using technologies that already exist. Urgent and coordinated action from all actors is needed to accelerate decarbonisation and ensure an achievable path to climate neutrality.

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