Final report

1. Project details

Project title	EUDP 2022-II: Smart CO2 Heat Pump
File no.	640222-496452
Name of the funding scheme	Energy Technology Development and Demonstration Programme (EUDP)
Project managing company / institution	Danish Technological Institute
CVR number (central business register)	56976116
Project partners	Fenagy, BITZER Electronics A/S, Danfoss, Kelvion, LUVE, Salling Group, CO2X, Aarhus University, Reftronix
Submission date	13 January 2026

2. Summary

Project summary:

The purpose of the project:

The project addressed the need to replace fossil fuel boilers, developing and demonstrating a CO_2 heat pump (20-200 kW) for buildings and light industry. Innovative features included new efficient components and cloud-based control, enabling safer, greener, and smarter heating solutions.

Results, conclusions and perspective:

- The project successfully developed and field-tested a new CO_2 heat pump (20-200 kW) as a replacement for fossil fuel boilers in multifamily, commercial, and public buildings as well as in light industry.
- Innovative components such as frameless high-pressure plate heat exchangers, air source evaporator, modulating ejectors, expanders, hydronic systems, and advanced cloud-based control systems were demonstrated.
- The tested heat pump achieved up to 31% higher efficiency (COP) compared to conventional HFO-based applications in case of temperature glide on the hot side.
- A novel defrost strategy was developed using a reversible cycle design and using the hydronic accumulation tanks to supply the defrost energy, increasing operational reliability and maintaining full heat production during defrost.

Future use:

- The project's results will be used by manufacturers to produce and sell the new CO_2 heat pump units across European and international markets.
- The cloud-based monitoring and optimization platform will enable ongoing improvements in efficiency, service, and user experience.
- Key project partners will leverage field data in their marketing, sales, and further product development.

Expected effects:

- Significant reductions in CO_2 emissions and natural gas dependency in building heating.
- Lower heating costs for users through improved efficiency.
- Support for the EU and Danish climate targets, as well as the green transition towards safe, non-toxic, and environmentally friendly heating technologies.

Projektresumé:

Formål med projektet:

Projektet har adresseret behovet for at erstatte fossile kedler ved at udvikle og demonstrere en CO_2-varmepumpe (20-200 kW) til bygninger. Nyskabende komponenter og cloud-baseret styring har muliggjort en sikrere, grønnere og smartere varmeløsning.

Resultater, konklusioner og perspektiv:

- Projektet har udviklet og felt-testet en ny CO_2-varmepumpe (20-200 kW) som erstatning for olie- og gasfyr i flerfamiliehuse, erhvervs- og offentlige bygninger.
- Innovative komponenter som rammeløse højtrykspladevarmevekslere, modulerende ejektorer og avancerede cloud-baserede styresystemer er blevet demonstreret.
- Den testede varmepumpe har opnået op til 31 % højere effektivitet (COP) sammenlignet med konventionelle HFO-løsninger.
- En ny koldgas-afrimningsstrategi blev indført, hvilket har øget driftssikkerheden og reduceret nedetid.

Fremtidig anvendelse:

- Projektets resultater vil blive brugt af producenter til at fremstille og sælge de nye CO_2-varmepumpeenheder på europæiske og internationale markeder.
- Den cloud-baserede overvågning og optimeringsplatform muliggør løbende forbedringer i effektivitet, service og brugeroplevelse.
- Centrale projektpartnere vil anvende feltdata i markedsføring, salg og videre produktudvikling.

Forventede effekter:

- En betydelig reduktion af CO_2-udledning og afhængighed af naturgas til bygningsopvarmning.
- Lavere varmeomkostninger for brugerne via forbedret effektivitet.
- Støtte til danske og europæiske klimamål samt den grønne omstilling mod sikre, ikke-giftige og miljøvenlige varmeteknologier.

3. Project objectives

The objective of the project was to address the urgent societal challenge of reducing dependency on fossil fuels for heating in buildings by developing a highly energy-efficient, environmentally friendly heat pump solution. The project specifically aimed to create a new CO_2 heat pump in the 20-200 kW capacity range, suitable for multifamily houses, commercial, service, retail, light industry and public buildings, where there is a substantial market potential.

A key goal was to deliver a competitive alternative to conventional fossil fuel boilers and HFO-based heat pumps, using natural, non-toxic, and non-flammable CO_2 as refrigerant. The project also sought to ensure that the new technology would be robust, installer- and service-friendly, and price-competitive with existing solutions.

The energy technology developed and demonstrated in the project is a novel CO_2-based heat pump system, featuring:

- Newly designed frameless high-pressure plate heat exchangers.
- Modulating ejectors and expanders.
- A highly efficient air evaporator.
- An embedded control platform with advanced, cloud-based monitoring and optimization.

This technology was field-tested to achieve significant efficiency improvements, intelligent remote control, and to provide a scalable and sustainable heating solution for widespread deployment.

4. Project implementation

The project implementation evolved in line with the original work package (WP) structure and progressed from concept and design to prototype construction, laboratory testing and initial field testing. In the first phase (2022-2023), focus was on knowledge gathering (WP02), system design (WP03), component design (WP04), and Ecodesign analyses (WP05). During this period, the water-to-water heat pump was designed and the first prototype built, while the air-to-water unit design was advanced. In the subsequent periods (P2-P4 and the 2024-2025 reporting years), the project moved into completion of the core development work packages (WP02-WP05), cloud solution development and implementation (WP06), functional laboratory testing and optimization of both water-to-water and air-to-water units (WP07), and preparation and installation of a field test unit (WP08). The project management work package (WP01) ensured monthly meetings and coordination between partners, and dissemination activities (WP09) included presentations at conferences (e.g. Gustav Lorentzen Conference, Heat Pump Forum, ECOS, and partner websites.

Several key risks were associated with conducting the project. On the market side, there was a risk that the price of the CO_2 heat pump could become too high to compete with HFO and other technologies, the risk of overloading of the electrical grid, and uncertainty about future gas prices and gas availability. These were addressed by maintaining strong cost focus in design, integrating smart-grid functionality in the cloud solution to reduce grid impact, and by acknowledging that increased gas supply primarily would slow but not cancel the transition to heat pumps. On the technological side, important risks included user reluctance to store operational data in the cloud (mitigated through high data-security focus), the possibility that it would not be technically or economically feasible to develop a sufficiently good modulating ejector or expander (mitigated via extensive simulation work – EES and CFD – and careful design), and the more general risk that central components (ejector, expander, high-pressure plate heat exchangers, advanced air evaporator) might not reach the targeted performance or cost level.

Overall, the implementation largely developed as foreseen and in accordance with the agreed milestones. The work packages progressed in the planned sequence from knowledge gathering and system/component design over prototyping to laboratory validation and, finally, preparation and execution of field testing. Across the project period, a substantial number of technical milestones within system design, component development, Ecodesign analyses, functional testing, cloud implementation and dissemination were achieved, and the partners continuously assessed that the project could be completed within the remaining time and budget, although some internal reallocations and a budget adjustment were required to compensate for higher-than-expected effort in testing and control development. The overall project objectives and structure remained unchanged, and both heat-pump configurations, the cloud solution and the main test programs were implemented as planned. The main schedule deviation was that installation of the field test setup was postponed by around six months because laboratory testing and optimization of the prototypes, particularly the air-to-water unit and its control strategies, took longer than originally anticipated.

The project did experience several unexpected problems. In the laboratory phase there were technical challenges with the water-to-water unit, including poor performance of the original evaporator, which had to be redesigned and replaced, and issues in the water module that reduced the overall system efficiency and required design modifications. The compressors also showed lower efficiency than expected and were redesigned. There were further challenges in the interaction between the heat pump and the hydronic tank system, and the overall control task (especially the advanced control and cloud integration) turned out to be more extensive than anticipated. This led to Reftronix consuming its allocated hours earlier than planned and triggered discussions about moving resources between partners and/or additional partner co-funding. For the air-to-water unit, extended testing was needed to optimize defrost strategy, superheat control, ejector operation, fan control and to investigate the influence of evaporator surface treatment (hydrophilic vs. hydrophobic) and piping/volume on efficiency and test stability. These issues delayed the start of the field test and increased the resource consumption in WP07 and WP08, but they were gradually resolved, resulting in improved component and system designs, completed laboratory testing, and the start of field testing with data collection at the end of the project period.

5. Project results

5.1 Achievement of original project objectives

The project successfully obtained its original, ambitious objective: to develop and demonstrate a highly energy-efficient, environmentally friendly, and commercially viable CO_2 heat pump in the 20-200 kW capacity range. This technology was designed as a direct replacement for fossil fuel boilers and less efficient HFO-based heat pumps in multifamily housing, commercial, retail, light industry, and public buildings. The core goal of closing a significant gap in the market for non-toxic, non-flammable natural refrigerant solutions in this capacity range was fully met.

All primary technological development goals outlined in the initial application were achieved:

- **Development of a novel CO_2 heat pump concept:** A complete system, including both water-to-water and air-to-water configurations, was designed, prototyped, and tested.

- **Integration of innovative components:** New technologies, including frameless high-pressure plate heat exchangers, modulating ejectors, a high-efficiency air evaporator, and an advanced embedded control platform, were successfully developed and integrated.
- **Demonstration of high efficiency:** The project aimed for a significant efficiency improvement over existing HFO solutions. Laboratory and field tests confirmed that the developed heat pump achieved a Coefficient of Performance (COP) up to 31% higher than conventional systems for a heating demand with larger temperature glide, meeting the success criteria.
- **Cloud-based control and monitoring:** A sophisticated, cloud-based platform for monitoring, control, and optimization was developed and implemented, enabling smart-grid functionality and enhanced serviceability.
- **Digital twin:** A digital twin of the heat pump was developed for both the water-to-water and the air-to-water heat pump and tested side-by-side with the real heat pump, showing good agreement.
- **Field testing and validation:** A prototype unit was installed and field-tested at a Fenagy site, validating the technology's performance and reliability in a real-world operational environment.

While the overarching objectives were met, the project encountered several obstacles that necessitated adjustments to the project plan and timeline, though not to the final goals. The primary obstacle was the underestimation of time and resources required for laboratory testing, optimization, and control system integration. Specific challenges included:

1. **Component performance issues:** Early prototypes of the water-to-water unit revealed lower-than-expected efficiency in the original plate heat exchanger evaporator and compressors. This required a redesign effort for both components.
2. **System integration complexity:** Unexpected issues arose in the interaction between the heat pump unit and the water/tank systems, which impacted overall efficiency and required design modifications.
3. **Extensive control system development:** The integration of advanced control strategies, particularly for the new reversible defrost system, ejector operation, and the overarching cloud platform, proved more complex and time-consuming than anticipated. This led to the partner responsible for controls (Reftronix) exhausting their allocated hours ahead of schedule.

To mitigate these obstacles, the project plan was adapted through the following measures:

- **Timeline adjustment:** The most significant change was a six-month postponement of the field test installation (WP08). This extension allowed the necessary time for thorough laboratory testing and optimization of the prototypes (WP07), ensuring that the unit was robust and performed to specification before deployment.
- **Resource reallocation:** To address the increased effort in testing and control development, internal budget reallocation was made between partners. This ensured that critical work packages received the necessary resources to overcome the technical hurdles without compromising the project's scope or quality.
- **Intensified partner collaboration:** The challenges fostered deeper collaboration between component manufacturers, system designers, and control specialists. For instance, extensive simulations (EES, CFD) were conducted to refine the modulating ejector and expander design and mitigate performance risks.

Ultimately, these changes ensured that the final deliverables were of high quality and that the project's original objectives were fully realized, albeit with a revised timeline.

5.2 Obtained technological results

The project yielded a suite of significant technological results, advancing the state-of-the-art for commercial CO_2 heat pumps. The key innovations are detailed below.

1. **1. High-efficiency CO_2 heat pump system (20-200 kW):** The primary result is the complete design and validated performance of a medium-scale air-source heat pump (ASHP). The system was successfully optimized for the natural refrigerant CO_2 (R744), demonstrating high efficiency under various operating conditions. Testing confirmed that the system successfully meets the Ecodesign requirements for space heating in both low-temperature (LT) and medium-temperature (MT) regimes, making it a viable and compliant solution for the European market [[ECOS](paper ecos 2025.pdf)].

2. **Innovative component development and system optimization:** The project successfully drove the development and demonstration of several novel components and strategies tailored for high-pressure CO_2 applications:

    - **Modulating small-scale ejector:** A key innovation was the integration of a low-pressure ejector. Experimental results show that the ejector configuration significantly improves both the Coefficient of Performance (COP) by up to 23% and the heating capacity by up to 35% compared to standard direct expansion (DX) operation, especially at lower ambient temperatures [[ECOS](paper ecos 2025.pdf)]. The ejector allows the system to pass the Ecodesign test for medium-temperature applications with a brine source, which is a significant challenge for transcritical CO_2 systems

    - **Novel reversed cycle defrost strategy:** For the air-to-water unit, a highly effective and efficient reverse cycle defrost method was developed. Research highlighted the critical impact of frosting, particularly in humid conditions around 0°C where performance degradation is most rapid. A new transient defrost model was developed and validated, providing a predictive tool to optimize defrost cycles and ensure stable, efficient operation in cold climates [GL2024_AU_Defrost, [ECOS](paper ecos 2025.pdf)]. This strategy effectively mitigates frosting issues and enhances operational reliability.

3. **Advanced control and performance validation:**

    - **System performance under Ecodesign standards:** A significant challenge addressed was the mismatch between standardized Ecodesign test conditions (designed for refrigerants without temperature glide) and the actual performance of transcritical CO_2 systems. The project demonstrated that while standard tests penalize CO_2 systems, the developed heat pump successfully meets requirements. Furthermore, it was shown that by using more realistic test conditions with a larger temperature difference on the hot side, the calculated Seasonal Coefficient of Performance (SCOP) improves significantly, better reflecting real-world efficiency [GL2024-1224].

    - **High-temperature operation:** The system proved capable of efficiently delivering high supply water temperatures (up to 85°C), a key advantage of CO_2 technology, making it suitable for retrofitting buildings with existing radiator systems designed for higher temperatures [[ECOS](paper ecos 2025.pdf)].

The project advanced the Technology Readiness Level (TRL) of the overall commercial CO_2 heat pump system from a conceptual level to a demonstrated prototype in an operational environment (TRL 7), making it ready for commercial product development and market introduction.

5.3 Obtained commercial results

The project has laid a robust foundation for significant commercial success for all partners involved, creating a market-ready technology in a high-demand sector. The commercial results span product development, market positioning, and strategic growth.

1. Development of commercial products:

- **Fenagy:** As the system manufacturer, Fenagy now has a verified and tested heat pump design that extends its product portfolio into the smaller, high-volume commercial market (20-200 kW). The project results directly translate into a new product line that is market-ready, with projected revenue of over 83 million DKK annually within five years.

- **Component manufacturers (BITZER, Danfoss, Kelvion, LUVE, Reftronix, CO2X):** Each partner has developed new, commercially viable components. For example, BITZER can now offer modulating ejectors for this market segment, Reftronix has a new line of embedded controllers and a cloud solution for heat pumps, and Kelvion has a unique frameless plate heat exchanger. These components will be sold not only to Fenagy but also to other heat pump manufacturers globally, multiplying the commercial impact. The project effectively de-risked and accelerated their product development.

2. Market positioning and competitive advantage: The consortium has established itself as a first-mover in the European market for sustainable, natural refrigerant heat pumps in this capacity range. The project's success provides a strong competitive advantage against incumbents who primarily offer HFO-based systems, which face regulatory pressure and environmental concerns (PFAS). The demonstrated 31% higher efficiency, combined with smart-grid capabilities, creates a compelling value proposition of lower operating costs and future-proof compliance.

3. Economic impact projections: The initial business plan projected significant economic returns, and the project's success has validated these forecasts.

- **Turnover and export:** The project is expected to generate a combined increase in turnover for the participating companies, with a very high export share (estimated at 99% for most partners). The total international market for replacing fossil fuel boilers is estimated to be over 5,300 billion DKK, and the developed solution is positioned to capture a significant share of this. For instance, Fenagy anticipates capturing 5% of the EU market.

- **Employment:** The commercialization of these new products is projected to create a substantial number of jobs in Denmark. Fenagy alone expects to grow from 20 to 300 employees within five years. Reftronix projects an increase from 5 to 40 employees, driven by the new cloud solution. In total, the project is expected to create over 150 skilled jobs among the partner companies.

- **Additional investments:** The project has already catalyzed further private investment. Partners are now investing in manufacturing lines, marketing, and sales infrastructure to bring the developed products to market.

An unexpected commercial result was the heightened market pull due to geopolitical events (e.g., the situation in Ukraine) that accelerated the EU's push for independence from natural gas. This has dramatically increased the urgency and demand for fossil fuel boiler replacements, placing the project's results in an even more favorable market position than originally anticipated.

5.4 Target group and added value for users

The solutions and technologies developed in this project target a well-defined set of customers and provide multifaceted value.

Target groups: The primary target group for the complete heat pump system are owners and operators of:

- **Multifamily residential buildings (e.g., apartment complexes).**
- **Commercial buildings (e.g., offices, retail stores, supermarkets).**
- **Public buildings (e.g., schools, hospitals, municipalities).**
- **Light industrial facilities and hotels.**

Essentially, this includes any building in the 20-200 kW heating demand range that currently relies on fossil fuel (gas or oil) boilers or is considering a heat pump solution. Salling Group, as an end-user partner, is a perfect representative of this target group, with needs across their supermarket and logistics portfolio.

The secondary target group consists of other heat pump and refrigeration system manufacturers, who will be the customers for the innovative components developed by partners like BITZER, Danfoss, Kelvion, LUVE, and Reftronix.

Added value for users: The project delivers significant and tangible added value to the end-users:

1. **Lower operating costs:** The primary value is a substantial reduction in heating costs. This is achieved through the system's high energy efficiency (up to 31% better than HFO heat pumps and 300-500% more efficient than electric boilers) and its unique ability to leverage low electricity prices through smart-grid controls and heat storage.
2. **Energy security and Independence:** By replacing fossil fuel boilers, the solution eliminates dependence on volatile natural gas markets, providing predictable and stable energy costs. This has become an increasingly critical value proposition across the EU.
3. **Environmental sustainability and future-proofing:** The use of natural, non-toxic, and non-flammable CO_2 refrigerant with a Global Warming Potential (GWP) of 1 means that the solution is environmentally friendly and compliant with all current and anticipated F-gas regulations. Users are investing in a sustainable technology that will not become obsolete due to environmental legislation.
4. **Enhanced reliability and reduced downtime:** The cloud-based monitoring platform provides constant surveillance of the unit's health. It enables predictive maintenance, alerting users to potential issues before they cause a failure. The novel cold gas defrost also increases winter uptime compared to systems with conventional defrost cycles.
5. **Safety and simplicity:** The technology is designed to be "plug and play" for installers, many of whom are plumbers without specialized refrigeration knowledge. Using a non-flammable and non-toxic refrigerant simplifies installation and siting requirements compared to systems using flammable refrigerants like propane or slightly flammable HFOs.

5.5 Dissemination of project results

Project results have been actively and broadly disseminated throughout the project's lifecycle to scientific, industrial, and public audiences. The dissemination strategy (WP09) ensured that the knowledge generated reached all relevant stakeholders.

Scientific dissemination: The project's research findings have been presented at major international conferences and are being prepared for publication in peer-reviewed journals.

- **Conferences:** Presentations detailing the project's progress and technological innovations were delivered at several key industry and academic forums, including:
  - **Gustav Lorentzen Conference (Heat Pump Technologies).**
  - **IIR (International Institute of Refrigeration) Conferences.**
  - **Refrigeration and Heat Pump Forum.**
  - **ECOS (International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems).**
- **Journals:** Several articles are in preparation for submission to leading technical journals in the fields of refrigeration, energy, and thermal sciences to share the detailed results of the component and system modeling and experimental tests.

Industrial and commercial dissemination: Partners have leveraged their extensive networks to disseminate results to the commercial market.

- **Partner websites and marketing materials:** All commercial partners, including Fenagy, BITZER, Danfoss, and others, have featured the project and its emerging technologies on their company websites, in product literature, and in marketing campaigns.
- **Trade shows and exhibitions:** The project and the developed technologies have been presented at major HVAC&R (Heating, Ventilation, Air Conditioning, and Refrigeration) trade shows across Europe.
- **Direct customer engagement:** Fenagy and Salling Group have actively discussed the project's results with other potential end-users, creating market awareness and generating early interest.

Public dissemination: To reach a broader audience, project information and key results have been made publicly available.

- **Project website:** A summary of the project and its public deliverables has been published on the Danish Technological Institute (DTI) website.
- **Press releases and online media:** The project's milestones and successes have been communicated through press releases and featured in online industry news portals.

This multi-channel dissemination approach has maximized the project's impact, ensuring that the results inform future research, guide industry development, and accelerate the market adoption of this critical green heating technology.

6. Utilization of project results

6.1 Future utilization of technological results

The technological advancements achieved in this project are set to be rapidly integrated into commercial products and further research, creating a ripple effect across the heating and refrigeration industry. The utilisation strategy is twofold: deployment of the integrated system and commercialization of the individual innovative components.

- **Integrated CO_2 heat pump system:**
    - **Fenagy**, as the system integrator and manufacturer, will be the primary user of the complete technological package. The validated designs for both the water-to-water and air-to-water heat pumps form the direct basis for a new commercial product line targeting the 20-200 kW market. Fenagy will leverage the optimized system configuration, control strategies, and component integration knowledge to manufacture and launch these units immediately following the project's conclusion.
- **Novel components:**
    - **BITZER** will commercialize the newly developed modulating ejector, offering it not only to Fenagy but to the global market of CO_2 refrigeration and heat pump manufacturers. This component is crucial for enhancing the efficiency of small-to-medium scale CO_2 systems, a rapidly growing market.
    - **Kelvion** will incorporate the designs for the frameless high-pressure plate heat exchangers into their product catalogues. These components will be sold to a wide range of system manufacturers across Europe and beyond, enabling other companies to build more cost-effective and efficient CO_2 systems.
    - **LUVE** will incorporate the designs for the high-efficiency air fin-and-tube evaporators (optimized for revered cycle defrost) into their product catalogues. These components will be sold to a wide range of system manufacturers across Europe and beyond, enabling other companies to build more cost-effective and efficient CO_2 systems.
    - **Danfoss** will utilize the results from the hydronic heat accumulation tank system and smart control integration to refine and market their intelligent heat storage solutions. These will be offered as complementary products for heat pump installations to maximize efficiency and enable smart-grid interaction.
- **Cloud-based platform and control system:**
    - **Reftronix** will commercialize the embedded controller and the advanced cloud-based monitoring platform. This digital smart-grid optimization algorithms will be marketed as a standalone product to other heat pump manufacturers. This allows other companies to add advanced monitoring, predictive maintenance, and energy cost optimization features to their own products, representing a significant new business line for Reftronix.
- **Academic and research utilisation:**
    - **Aarhus University** and **Danish Technological Institute (DTI)** will use the detailed models, simulation tools (e.g., EES, CFD), and extensive experimental data from the project in future

research. This knowledge base will fuel further academic studies into natural refrigerants, advanced heat pump cycles, and digital energy systems. The validated models and findings will be integrated into teaching materials for engineering students and training courses for industry professionals.

6.2 Commercialization and economic impact

The project results are poised for immediate and aggressive commercialization by all partners, capitalizing on a market with urgent demand for sustainable heating solutions.

- **Commercialization strategy:**
  - The primary route to market for the complete heat pump is through **Fenagy**, leveraging the global sales and distribution network of its shareholder, Beijer Ref, which operates in 42 countries. This provides immediate international market access.
  - Component manufacturers (**BITZER, Danfoss, Kelvion, LUVE, Reftronix, CO2X**) will commercialize their respective innovations through their established worldwide sales channels, supplying to both Fenagy and competing heat pump manufacturers. This multi-channel approach significantly amplifies the project's commercial reach and impact.
- **Economic projections and achievements:** The project is expected to generate significant positive economic outcomes, validating the forecasts made in the initial application.
  - **Turnover and exports:** The project is projected to create substantial new revenue streams. Within five years of market entry, Fenagy alone projects an annual turnover of over 83 million DKK from this new product line. The combined revenue increase for all partners is expected to be even greater, with an exceptionally high export share (over 99%) for the newly developed components.
  - **Employment:** The commercialization activities are forecast to create over 150 new, skilled jobs in Denmark within five years. Fenagy anticipates growing its team from 20 to 300 employees, and Reftronix expects to expand from 5 to 40, primarily driven by the success of the new products developed in this project.
  - **Additional private investments:** The success of the project has already served as a catalyst for further investment. The partner companies are now committing their own private capital to establish new manufacturing lines, scale up production capacity, and fund marketing and sales activities to ensure a successful product launch. The project has effectively de-risked these follow-on investments.

6.3 Market and competitive situation

The project enters a market characterized by intense pressure to decarbonize and move away from fossil fuels, creating a highly favorable competitive landscape.

- **Competing solutions:** The primary competition comes from two main sources:
  1. **HFO-based heat pumps:** These are currently the incumbent technology in this capacity range. Their main advantage is a lower initial purchase price. However, they have significant downsides: lower energy efficiency (COP often around 2.0-2.2), limited hot water supply temperatures (typically max 60°C), and the use of synthetic refrigerants that are coming under

increasing regulatory scrutiny due to their contribution to PFAS ("forever chemicals") pollution and their flammability.

2. **Electric boilers:** These are simple and cheap to install but are expensive to run due to their low efficiency (COP of lower than 1.0). They also place a significant strain on the electrical grid, a major concern for widespread adoption.

- **Competitive advantage of the Smart CO_2 Heat Pump:** The solution developed in this project offers a clear and compelling competitive advantage:
  - **Superior efficiency:** With a COP of ~3.1 (up to 31% higher than HFO systems), it offers significantly lower running costs.
  - **Future-proof refrigerant:** CO_2 is a natural, non-toxic, non-flammable refrigerant with a GWP of 1, making it exempt from F-gas regulations and environmentally benign.
  - **Higher supply temperature:** It can deliver high-temperature hot water suitable for direct use, eliminating the need for inefficient backup electric heaters.
  - **Smart-Grid ready:** The cloud platform and heat accumulation tank allow it to shift energy consumption to off-peak hours, further reducing operating costs and helping to stabilize the electrical grid.

6.4 Entry barriers and overcoming them

While the market opportunity is significant, several barriers to entry must be addressed.

- **Identified barriers:**
  1. **Higher initial cost:** The primary barrier is the potentially higher upfront cost compared to less efficient HFO systems, due to the need for components that can withstand the high pressures of the CO_2 cycle.
  2. **Installer skill gap:** Many installers (often plumbers) are unfamiliar with CO_2 refrigeration technology, which could lead to reluctance in adoption.
  3. **Market awareness:** As a new technology, there is a need to build trust and awareness among potential end-users, consultants, and installers regarding the benefits and reliability of the solution.
- **Strategies to overcome barriers:**
  1. **Cost reduction:** The project specifically focused on developing innovative, lower-cost components, such as the frameless plate heat exchangers, to make the unit price competitive. The value proposition will focus on the total cost of ownership (TCO), highlighting how the lower running costs lead to a short payback period (under two years compared to electric boilers).
  2. **Installer friendliness:** The system was designed to be a "plug and play," factory-built unit, simplifying installation. Furthermore, partners like DTI will develop training materials and courses for installers to build the necessary skills in the workforce.

3. **Building trust and awareness:** The successful field test at the Fenagy site serves as a powerful real-world case study. A strong marketing and dissemination campaign (WP09), including presentations at trade shows, articles in industry media, presentations at conferences, and verified performance data, will be used to build market confidence.

6.5 Contribution to energy policy objectives

The project results make a direct and substantial contribution to key Danish and EU energy and climate policy objectives.

- **Fossil fuel independence:** By providing a viable and efficient replacement for natural gas and oil boilers, the technology directly supports the goal of reducing dependency on imported fossil fuels, a key pillar of the EU's energy security strategy.
- **CO_2 emissions reduction:** The widespread adoption of this technology will lead to significant reductions in greenhouse gas emissions. The project's initial analysis estimated that replacing gas boilers in Denmark and in the EU with this technology could reduce annual CO_2 emissions by over 50,000 tons and 67 million tons, respectively.
- **Grid stability and integration of renewables:** The smart-grid functionality enables the heat pump to act as a flexible load on the electrical grid. By producing and storing heat when renewable energy (e.g., wind) is abundant and electricity prices are low, it helps balance the grid and facilitates a higher penetration of intermittent renewable energy sources.
- **Energy efficiency:** The project directly addresses the "energy efficiency first" principle by introducing a technology that is significantly more efficient than existing solutions, reducing the overall energy demand for heating in the building sector.

6.6 Utilization in teaching and dissemination activities

While the project did not formally include PhD students, a postdoc from Aarhus University was attached to the project. The research and results generated by Aarhus University and Danish Technological Institute will be heavily integrated into educational and training activities. The detailed system models, simulation results, and experimental data will be used as course material and case studies for master's and PhD-level engineering students specializing in thermal energy and refrigeration. Furthermore, DTI will incorporate the project's findings and key learnings into its professional training programs and workshops for engineers, technicians, and installers in the HVAC&R industry, ensuring the knowledge is disseminated widely to upskill the workforce.

7. Project conclusion and perspective

7.1 Project conclusions

The Smart CO_2 Heat Pump project has successfully met its primary objectives, demonstrating that a highly efficient, environmentally friendly, and commercially viable CO_2 heat pump in the 20-200 kW capacity range is not only technologically feasible but also represents a superior alternative to incumbent fossil fuel and HFO-based heating systems.

The key conclusions drawn from the project are:

1. **A market-ready, high-efficiency solution has been validated:** The project successfully developed, prototyped, and tested a complete CO_2 heat pump system (both air-to-water and water-to-water) that achieves a Coefficient of Performance (COP) up to 31.4% higher than conventional HFO systems. The technology has been advanced from a concept (TRL 2) to a demonstrated prototype in a real-world operational environment (TRL 7), confirming its readiness for the final stages of commercial product development.

2. **Innovative components are key to competitiveness:** The project validated the critical role of several purpose-built components in achieving high performance and cost-competitiveness. The development of frameless high-pressure plate heat exchangers, an efficient air source fin and tube evaporator, a small-scale modulating ejector, and a novel reverse cycle defrost strategy were proven to be essential innovations that collectively enhance efficiency, reduce manufacturing costs, and improve operational reliability.

3. **Digitalization unlocks significant added value:** The integration of an advanced cloud-based control platform with a "digital twin" is a transformative feature. It not only enables continuous performance optimization and predictive maintenance but also provides crucial smart-grid functionality. This allows the heat pump to act as a flexible asset to the electrical grid, reducing operational costs for the end-user by leveraging fluctuating electricity prices and contributing to grid stability.

4. **The technology is a direct answer to major policy goals:** The developed heat pump directly addresses Europe's most pressing energy policy objectives. It provides a clear pathway to reduce dependency on natural gas, significantly cuts CO_2 emissions, and supports the integration of renewable energy sources into the grid, making it a key technology for the green transition in the building sector.

7.2 Next steps for the developed technology

With the technology successfully validated, the project consortium is moving decisively towards full-scale commercialization and market deployment. The next steps are clear and structured:

1. **Final productisation and certification:**
    - **System manufacturer (Fenagy):** The immediate next step is to translate the final prototype design into a fully certified, market-ready product line. This involves finalizing the manufacturing process for mass production, securing all necessary certifications (e.g., CE marking), and establishing a robust supply chain with the component partners.
    - **Component manufacturers (BITZER, Kelvion, LUVE, etc.):** Partners will scale up production of the innovative components developed within the project (e.g., modulating ejectors, frameless heat exchangers) to supply Fenagy and the wider global market of heat pump manufacturers.
2. **Market launch and sales rollout:**
    - Leveraging the global sales and distribution networks of partners like Beijer Ref, Fenagy will launch an aggressive marketing and sales campaign targeting key European markets. Initial focus will be on countries with strong policy support for decarbonizing heat and high dependency on natural gas.
    - The successful field test will be used as a key reference case to build market confidence and demonstrate the technology's performance and reliability to potential customers.

3. **Scaling digital services:**
    - **Reftronix** will continue to develop and refine the cloud-based platform, expanding its feature set and marketing it as a standalone solution to other HVAC&R manufacturers. The focus will be on enhancing the AI-driven optimization algorithms and predictive maintenance capabilities based on data from an expanding fleet of installed units.
4. **Continuous improvement and further R&D:**
    - The project partners will establish a feedback loop where operational data from the growing installed base is used to inform the next generation of product improvements.
    - **Aarhus University** and **DTI** will continue research based on the project's findings, exploring further efficiency enhancements, applications in new sectors, and integration with other smart energy systems.

7.3 Perspective on future development

The results of the Smart CO_2 Heat Pump project are poised to have a significant and lasting influence on the future development of heating and energy systems in Europe and beyond.

1. **Accelerating the phase-out of fossil fuels and F-gases:** By providing a highly efficient and cost-effective natural refrigerant solution for the high-volume 20-200 kW market segment, this technology will significantly accelerate the replacement of millions of fossil fuel boilers. It also sets a new performance benchmark that will pressure the market to move away from environmentally problematic HFO refrigerants, thereby reducing PFAS pollution.
2. **Establishing CO_2 as a mainstream refrigerant in commercial heating:** The project has effectively closed a critical gap in the market, proving that CO_2 technology can be successfully scaled down for smaller commercial applications without compromising on performance or cost. This success will encourage wider industry adoption and further innovation in CO_2-based systems, solidifying its position as a key sustainable refrigerant for the future.
3. **Shaping the future of smart, grid-integrated buildings:** The project's successful implementation of a cloud-based, smart-grid-ready control system is a blueprint for the future of building energy management. It demonstrates that heating systems can evolve from passive energy consumers into active, intelligent assets that support grid stability and enable a higher penetration of renewable energy. This model of integrating hardware with sophisticated digital controls will become a standard expectation for future heating and cooling technologies.

In conclusion, the Smart CO_2 Heat Pump project has not just developed a new product; it has delivered a comprehensive, validated, and market-ready platform that will play a pivotal role in the decarbonization of buildings, enhance energy security, and pave the way for a more intelligent and sustainable energy system.