

Final report

1. Project details

Project title	Fremtidens Optimerede Reversible CO₂-køle- og varmepumpesystemer
File no.	64021-7016
Name of the funding scheme	EUDP 2021-II
Project managing company / institution	Danish Technological Institute
CVR number (central business register)	56976116
Project partners	<ul style="list-style-type: none">• Danish Technological Institute (DTI)• Fenagy• Bitzer• Danfoss• Kelvion• Güntner• Arla Foods• DTU (Technical University of Denmark)• ElCon
Submission date	24-09-2025

2. Summary

Project summary:

The purpose of the project

The project addressed the challenge of reducing the use of fossil fuel in industry by developing and demonstrating a large-scale, factory-built CO₂-based chiller/heat pump. It innovatively combined heating and cooling into one efficient system with digital monitoring for maximum performance.

Results, conclusions and perspective

Key results from the project:

- Developed and tested a high-capacity, reversible CO₂ chiller/heat pump that replaces separate systems for heating and cooling.
- Achieved up to 600% higher energy efficiency (COP 4-6) compared to conventional solutions.
- Designed advanced, cost-effective components, including new compressors, plate heat exchangers, a reversible air source fin and tube heat exchanger, industrial valves, ejectors, and expanders.
- Implemented cloud-based digital monitoring (IoT) and control to optimize performance and predict maintenance needs.
- Successfully demonstrated the unit in real-world industrial settings.

Use of results in the future:

- The technology is being commercialized for use in industry and in large buildings, enabling customers to both save energy and reduce costs.
- The digital monitoring platform will ensure long-term efficiency and reliability for users.

Expected effects from the technology:

- Significant reduction in fossil fuel consumption and greenhouse gas emissions (over 2 million tons CO₂ per year possible in 2041).
- Lower energy bills and improved competitiveness for users.
- Contribution to achieving national and EU climate goals by promoting electrification and energy efficiency in industry.
- Establishment of Denmark and partners as leaders in sustainable heating and cooling technology.

Projektresumé

Formålet med projektet

Projektet har adresseret udfordringen med at reducere fossilt brændstofforbrug i industrien ved at udvikle og demonstrere en stor, fabriksbygget CO₂-baseret køle-/varmepumpe. På en innovativ måde kombinerer løsningen opvarmning og køling i ét effektivt system med digital overvågning.

Resultater, konklusioner og perspektiv

Vigtigste resultater fra projektet:

- Udviklede og testede en højkapacitets-, reversibel CO₂-køle-/varmepumpe, der kan erstatte separate systemer til opvarmning og køling.
- Opnåede op til 600 % højere energieffektivitet (COP 4-6) sammenlignet med konventionelle løsninger.
- Designede avancerede, omkostningseffektive komponenter – herunder nye kompressorer, pladevekslere, reversibel luft-rør- og finnevarmeveksler, industrielle ventiler, ejektorer og expandere.
- Implementerede cloud-baseret digital overvågning (IoT) og styring for at optimere drift og forudsige vedligeholdelsesbehov.
- Enheden blev med succes demonstreret i industrielle anlæg under reelle driftsforhold.

Fremtidig anvendelse af resultaterne:

- Teknologien vil blive kommercialiseret til brug i industrien og større bygninger, så brugerne kan reducere både energi- og driftsomkostninger.
- Den digitale overvågningsplatform sikrer langvarig effektivitet og driftssikkerhed for brugerne.

Forventede effekter af teknologien:

- Betydelig reduktion af fossilt brændstofforbrug og drivhusgasudledning (potentiale for over 2 mio. tons CO₂ årligt i 2041).
- Lavere energiregninger og styrket konkurrenceevne for brugerne.
- Bidrag til nationale og europæiske klimamål gennem øget elektrificering og energieffektivitet i industrien.
- Styrkelse af Danmarks og partnernes position som ledende inden for bæredygtig varme- og køleteknologi.

3. Project objectives

The objective of the project was to address the challenge of reducing fossil fuel consumption in industry by developing and demonstrating a large-scale, factory-built CO₂-based chiller/heat pump system. This project aimed to provide a highly energy-efficient solution that combines both heating and cooling in one single unit, supported by advanced digital monitoring for optimal performance and reliability.

The developed and demonstrated energy technology is a high-capacity, reversible CO₂ chiller/heat pump. This system innovatively replaces separate heating and cooling installations, achieves significantly higher energy efficiency (COP 4-6), and incorporates state-of-the-art components such as new compressors, plate heat exchangers, reversible air source fin and tube heat exchanger, industrial valves, expansions valve controls, ejectors and expanders. The unit is further enhanced with a cloud-based digital (IoT) platform for real-time performance optimization and predictive maintenance.

4. Project implementation

How did the project evolve?

The project progressed through a series of defined work packages, with most activities carried out largely as planned. However, building the Danish Technological Institute test setup and installing the newly developed reversible gas cooler/evaporator proved more time-consuming and complex than anticipated, resulting in an 8-month delay to the project timeline.

Initial efforts focused on knowledge gathering and integrating end-user requirements into the design, followed by the development and assembly of the test unit. The project gained useful feedback from presentation of the concept at the Chillventa trade show, which was incorporated into further customization. Several technical components, such as a reversible air source fin and tube heat exchanger, new types of compressors, new high pressure plate heat exchangers, industrial valves, new control platform for expansions valves, industrial ejectors, expander, and control systems, were designed, built, and tested during the project period. Adjustments and redesigns, particularly of high-pressure plate heat exchangers, valves and ejectors, were necessary as issues arose, but subsequent tests showed improved and stable performance.

The risks associated with conducting the project.

Throughout the project period, several market and technology risks were identified and managed:

- **Market risks:** There was a risk that the developed solution could become too expensive compared to alternative heating or cooling systems, that component manufacturers might not continue development of large-scale CO₂ components, or that key partners might step away from commercializing the technology.
- **Technological risks:** One of the technical risks was that the reversible gas cooler/evaporator might not work both as a gas cooler and an evaporator. If so, separate components would be needed, reducing system efficiency and significantly increasing costs. Furthermore, achieving the expected efficiency gains from custom ejectors also posed a risk, addressed through extensive simulations and project partner experience. An additional technical risk was the complexity of reliably switching between running modes, such as transitioning between winter and summer operation, which could impact overall system performance and reliability.

Did the project implementation develop as foreseen and according to milestones agreed upon?

While early stages progressed in line with the project plan, some delays were experienced:

- The installation and testing of the IoT cloud and performance analysis systems (WP04) were delayed due to pending component integration on the test unit.
- Functional analyses (WP05) also lagged behind schedule due to unforeseen extensive work on the test rig. As a result, the finalization of these tests was pushed back by approximately eight months, which required an extension of the project period.
- Despite these challenges, redesigned and upgraded components have performed well in subsequent tests, and most issues have been resolved.

Did the project experience problems not expected?

Yes, a few unanticipated challenges arose:

- Some components, particularly electrical installation, high-pressure plate heat exchangers, compressors, and ejectors, required redesign due to operational issues discovered during initial tests.
- There were also challenges regarding oil supply to compressors, which were subsequently resolved.
- Cost overruns emerged for some of the partners, as building and testing the unit proved more expensive than anticipated for some of the project partners. Negotiations were carried out to reallocate some unused expenses and hours in the project among the companies involved.
- The transition from lab tests to field testing was delayed while a suitable field test location was secured by the extension of the project time.

Despite these challenges, the collaboration among partners has remained strong, with high engagement driven by a significant market demand for the solution being developed.

5. Project results

The FORCO₂ project has developed a novel large-scale system that can provide both heating and cooling simultaneously using CO₂ as the refrigerant. The central innovation is a fully reversible unit designed to serve industrial processes and large buildings where there is a demand for both cooling and heating at different times or even concurrently. This single system eliminates the need for separate installations for heating and cooling as is state-of-the-art shown schematically in Figure 1, reducing both energy waste and investment costs.

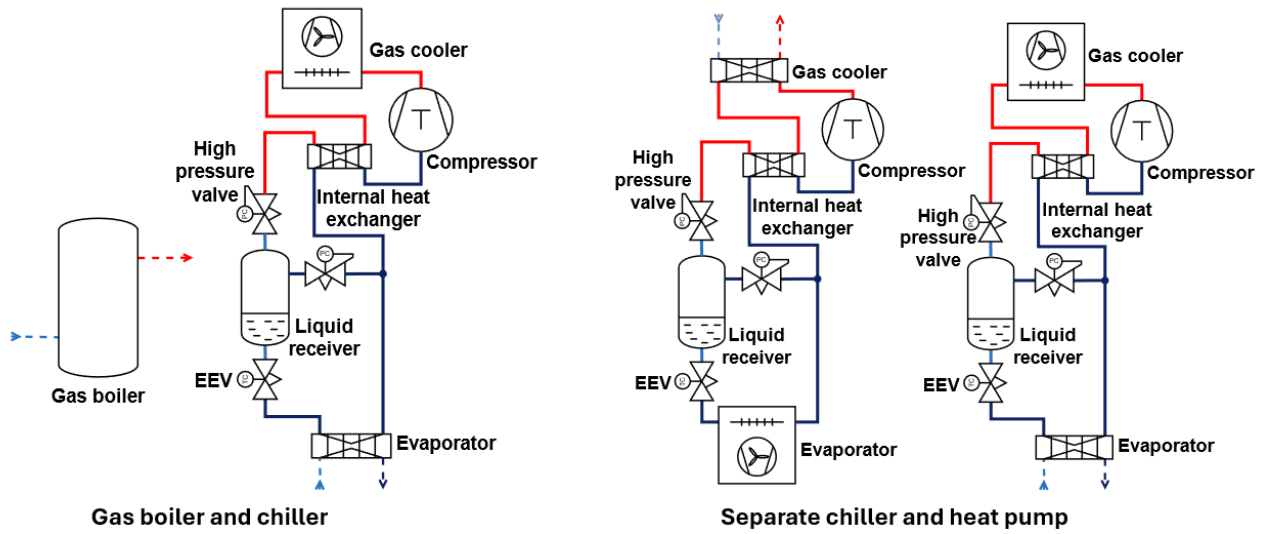


Figure 1: State-of-the-art solution for separate heating and cooling demands.

Pictures of the laboratory installation are shown in Figure 2 where the heat pump itself is shown on the left and the reversible air source fin and tube heat exchanger on the right.

At the heart of the system is an advanced air fin and tube heat exchanger that can function as either an evaporator or a gas cooler, depending on the operating mode (see Figure 2, right). This reversible heat exchanger is just one key component. The system also includes high-capacity, high-pressure plate heat exchangers for effective heat transfer and incorporates CO₂ ejectors that boost the overall system efficiency, especially during part-load operation. The system is modular and scalable, the tested prototype had a heating capacity of 1500 kW, and its output can be matched to different demands by adjusting the number of parallel compressors and ejectors, maintaining excellent efficiency across a range of operating conditions.



Figure 2: To the left is the heat pump that was developed in the project. To the right the reversible air source fin tube heat exchanger also developed in the project.

The FORCO2 system operates in four main modes, which are clearly illustrated in Figure 3 and Figure 4. These modes include heat pump mode using air as a heat source for pure heating operation (Mode 1), combined mode driven primarily by heating load with some simultaneous cooling (Mode 2), combined mode driven by cooling demand (Mode 3), where the reversible exchanger operates as a gas cooler, and pure chiller mode (Mode 4), focusing on cooling alone. The flexibility to switch between these modes allows the system to adapt dynamically to fluctuations in hot and cold-water requirements, always maximizing energy efficiency.

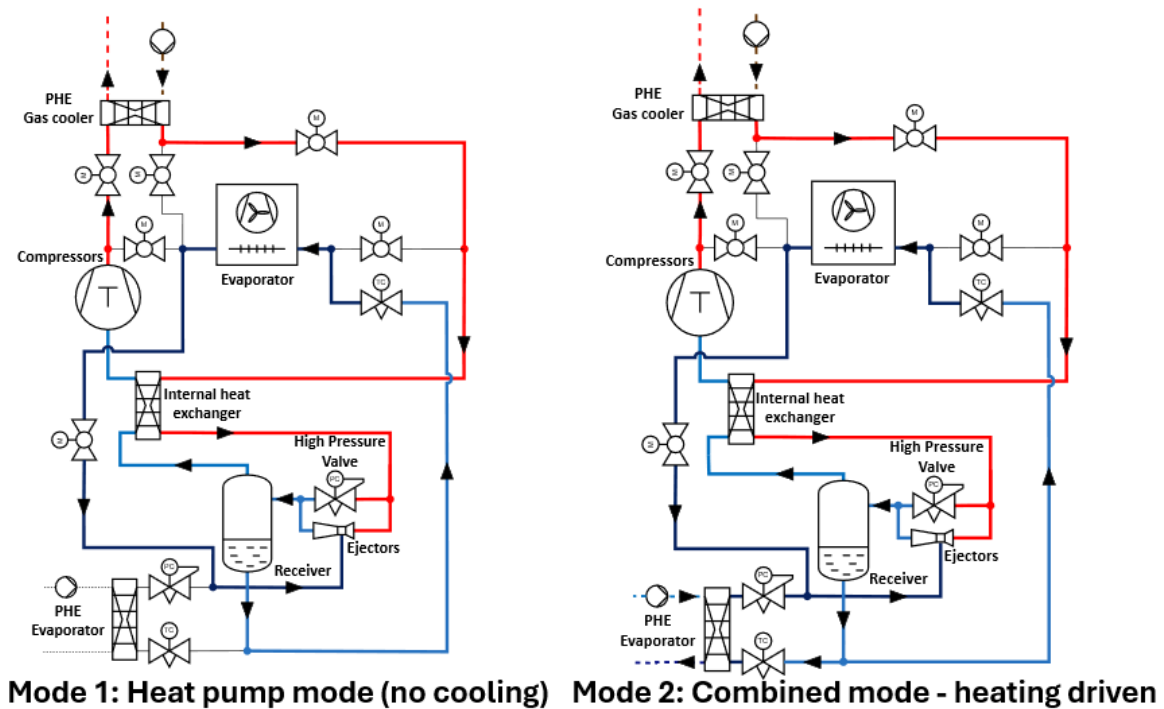


Figure 3: Running mode for a heat driven production.

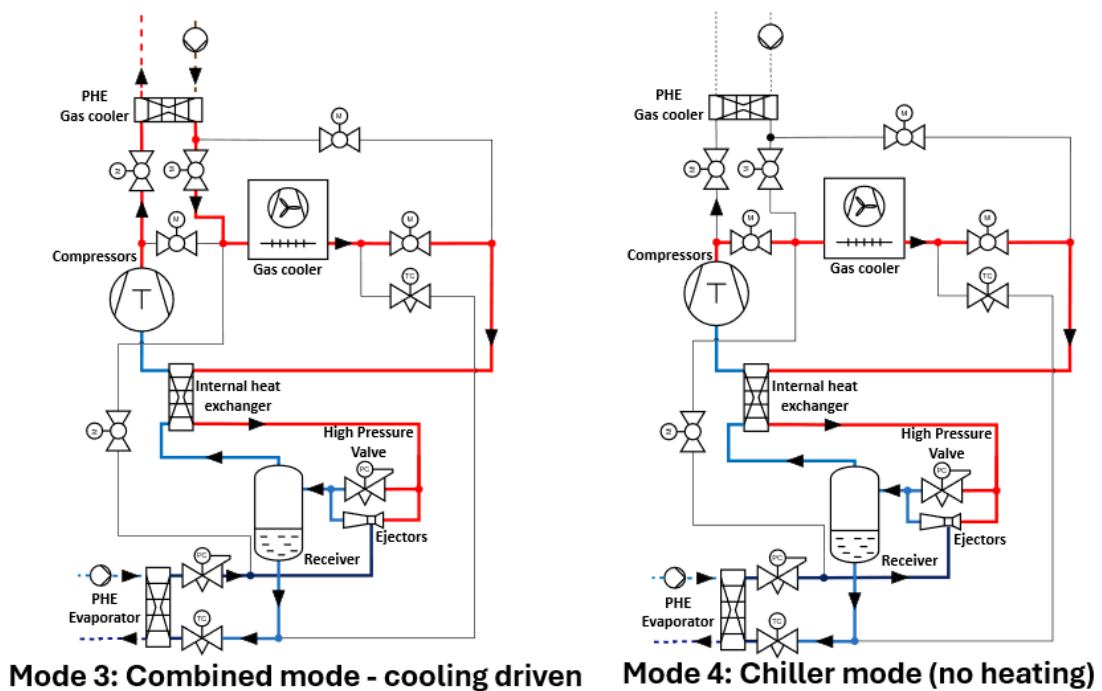


Figure 4: Running mode for a cold driven production.

Experimental validation at Danish Technological Institute demonstrated that the system could maintain stable with efficient operation across a wide range of loads and conditions. The integration of ejectors allowed efficient operation down to low part-loads, and the combined system consistently outperformed conventional setups that use separate equipment for heating and cooling. Importantly, continuous operation through the different running modes, such as switching between winter and summer operation, proved feasible through careful control system design. This allowed the heat pump to change modes smoothly and reliably, without needing to stop or restart the system, further improving operational flexibility and uptime.

Initial tests also revealed areas for further development, such as optimizing refrigerant charge management in pure chiller mode and refining defrost strategies to enhance reliability. Looking forward, the integration of thermal storage is seen as a key avenue for further increasing the system's energy efficiency and operational flexibility.

A major milestone in the project was the successful field testing and demonstration of the integrated CO₂ chiller/heat pump system at Velux, a leading Danish industrial partner, shown in Figure 5. The full-scale installation provided a rigorous real-world validation of the technology, confirming both technical robustness and operational efficiency under varying loads typical for industrial environments. During the test period, the system consistently delivered high coefficients of performance, seamlessly switching between heating and cooling modes to meet the facility's simultaneous demands. The digital monitoring platform enabled real-time performance tracking, further improving reliability. Data gathered from the Velux site has not only confirmed the energy savings and the emission reduction potential compared to conventional solutions but has also served as a credible market reference supporting commercial rollout. Feedback and operational experience from the Velux field test have directly informed subsequent system refinements, strengthened the project's outcomes, and accelerated market readiness.



Figure 5: The heat pump and air source heat exchangers at the field test site.

The FORCO2 project's technology represents a significant step forward in the use of CO₂ for integrated, large-scale heating and cooling applications. The combination of a reversible heat exchanger, advanced control strategies, and ejectors enables highly efficient, simultaneous provision of heating and cooling from one single system. Overall, the project has been very successful with excellent cooperation and strong collaboration among the project partners.

5.1 Achievement of project objectives

The intended outcome of the project was to create and demonstrate a groundbreaking, large-scale CO₂-based reversible chiller and heat pump system designed to set a new standard for energy efficiency and climate-friendly operation in industry and large residential buildings. The pathway toward this goal involved developing not only a highly integrated physical system, but also advanced digital control and monitoring, ensuring the solution's long-term reliability and commercial relevance.

The project succeeded in delivering these core objectives. The consortium can point to the following major achievements:

- **A fully integrated, factory-assembled CO₂ chiller/heat pump unit** was designed, manufactured, and successfully tested, both in laboratory conditions and in an industrial field environment at Velux.
- **System energy efficiency exceeded expectations**, with measured combined coefficients of performance (COP) in the range of 4 to 6, validating the anticipated energy savings compared to traditional separate heating and cooling systems.
- **Digital infrastructure was fully implemented:** An IoT-based cloud monitoring system and digital twin analytics consistently provided real-time performance insights, maintenance alerts, and efficiency tracking, supporting improved operational decisions throughout the equipment's lifetime.
- **The system demonstrated robust operation under real-world loads**, confirming its technical reliability, safety, and end-user value in an industrial setting. Changing operating modes from summer to winter seamlessly with all the intermediate modes was successfully validated.

While the overall targets were met, the project journey included several significant challenges:

- **Technical complexity and component delays:**
 - Developing industrial CO₂ ejectors, heat pump and expansion valve control, expanders, and high-pressure heat exchangers demanded new engineering capabilities.
 - Some key components required multiple design iterations or arrived later than forecast, compressing test and integration schedules.
- **System integration and operational hurdles:**
 - Ensuring oil management in compressors and reliable control across the full range of heating/cooling modes prompted additional lab work.
 - Operating challenges to start with for the industrial CO₂ ejectors that needed to be redesigned.
 - Challenges with corrosion in the gas cooler were challenging and took a lot of effort to investigate.
 - The gas cooler high-pressure heat exchanger broke down several times during testing and had to be replaced multiple times before stable operation was achieved.
- **Unexpected costs and resource requirements:**
 - The one-off nature of early prototypes increased manufacturing and assembly costs.

- The repeated removal and reinstallation of the gas cooler after breakdowns added significant unforeseen costs to the project.
- Balancing the project schedule in the face of supply delays demanded adaptive teamwork and ongoing resource allocation reviews.

To keep the project on track and meet its objectives, the consortium responded with several adaptive strategies:

- **Phased development and flexible scheduling:**

- Subsystem testing was prioritized where component delays were an issue, allowing learning and troubleshooting ahead of full system assembly. A separate test-rig for ejectors, valves, and expanders, shown in Figure 6, was built to enable thorough testing of these subsystems before integration.
- The project also required the design and construction of extensive and costly mixing loops in the test setup to simulate a variety of real-world operating conditions. These mixing loops, as illustrated in Figure 7, added significant complexity and additional expenses but were essential for achieving robust and realistic prototype evaluation.
- Project milestones were reviewed and adjusted as needed to avoid compromising quality or ambition.

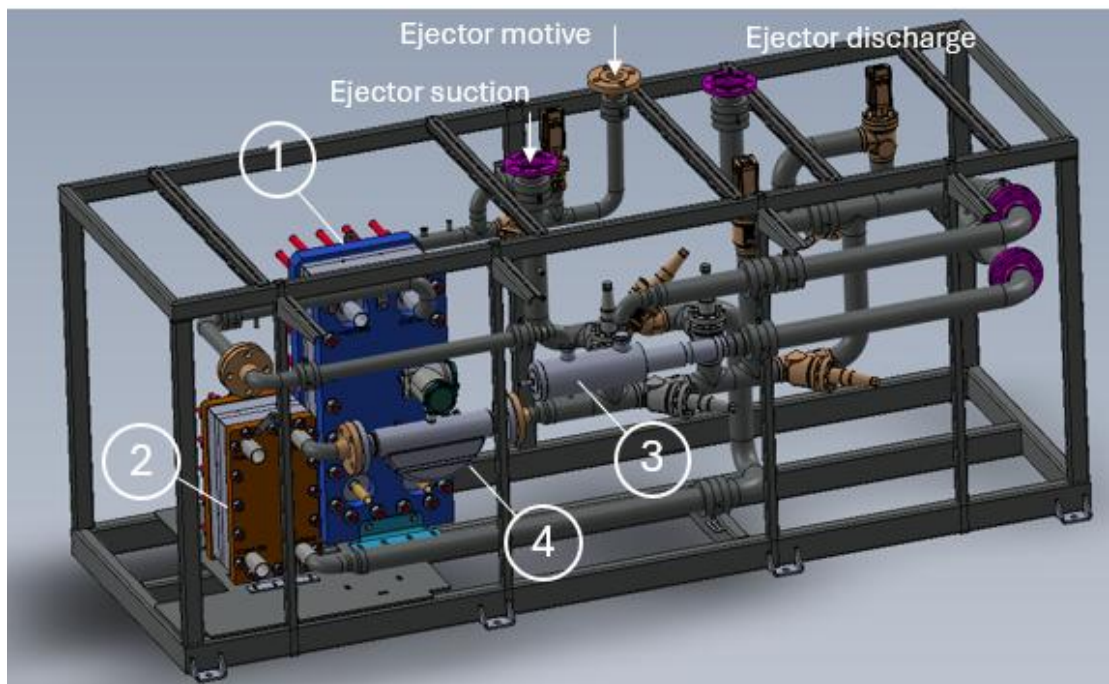


Figure 6: Ejector test rig. 1 – Motive flow heat exchanger, 2 – Suction flow heat exchanger, 3 – Ejector to be tested. 4 – flow meter.



Figure 7: Part of the mixing loops built for the testing in the project.

- **Intensive simulation-driven development:**
 - Advanced modeling, especially multiphase CFD (as described in Kanbur et al. 2023), was employed to validate concepts and refine ejector designs before physical prototypes were available.
- **Collaborative problem-solving:**
 - Regular technical meetings facilitated rapid communication between project partners, supporting swift troubleshooting and innovation.
- **Focused risk management and budget controls:**
 - Risks and cost overruns were managed through transparent reporting, shared burden among partners, and continuous pursuit of design-for-manufacture improvements.

The original objectives were fully obtained. Despite significant technical and logistical hurdles, adaptive planning and strong cross-partner collaboration delivered a market-ready product that advances both Denmark's climate goals and global best practice in industrial energy solutions. The project leaves behind not only a working field installation, but also a strengthened knowledge and supply chain ready for scaling and export.

5.2 Obtained technological results

This project led to a suite of technological advancements that together represent a step change for sustainable heating and cooling at industrial and large commercial scale. Several system innovations and component breakthroughs were developed, validated, and demonstrated under real-world conditions.

In Figure 8, an overview of the developed components in the reversible CO₂ heat pump system is shown. The photo illustrates the complete heat pump unit with all the major innovations highlighted. The image is a visual

summary of the project's technological achievements and collaborative development efforts across all major system components.

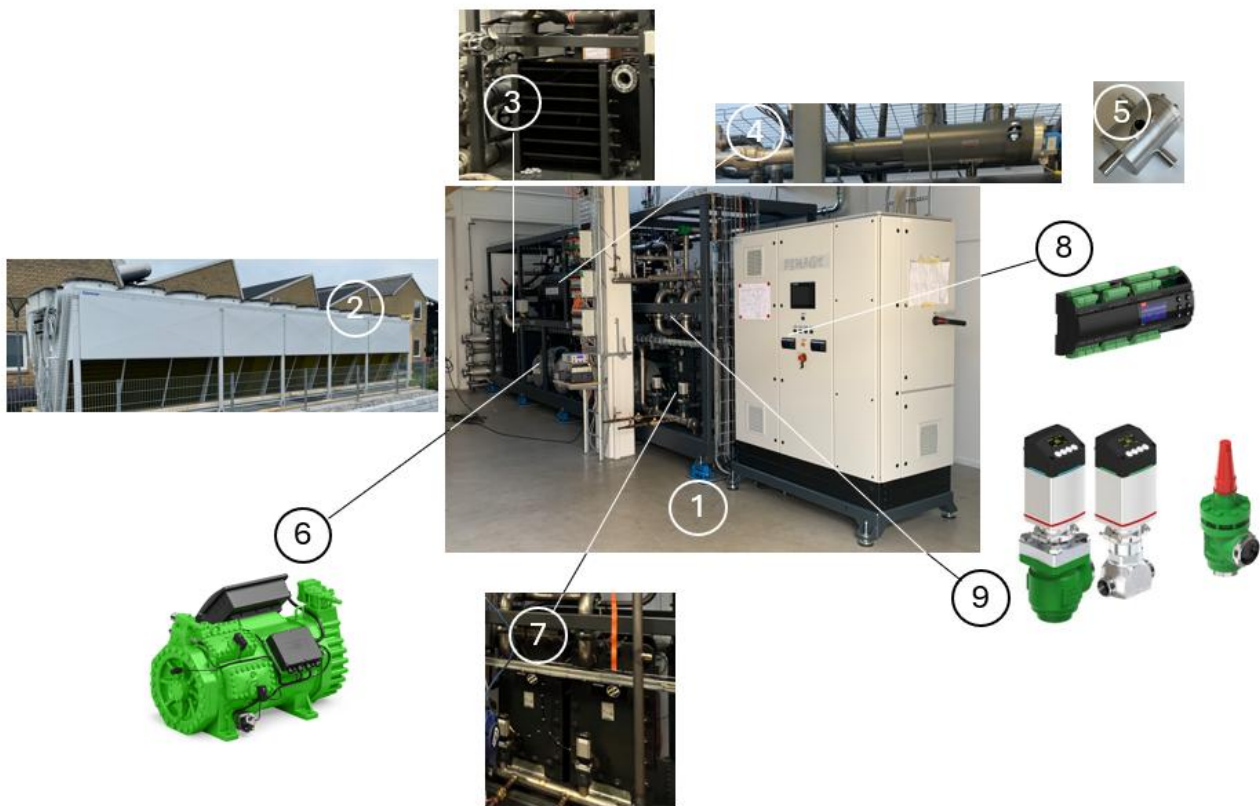


Figure 8: Overview of the developed components in the reversible CO₂ heat pump. 1 – Large industrial reversible CO₂ heat pump (Fenagy), 2 – Reversible air source fin and tube heat exchanger (Guentner), 3 – High pressure gas cooler plate heat exchanger (Kelvion), 4 – Industrial size ejector (Danfoss), 5 – Industrial size expander (CO2X), 6 – Large sized transcritical compressors (Bitzer), 7 – Large size plate heat exchanger evaporator (Kelvion), 8 – Control platform for ejectors and expansion valves (Danfoss), 9 – Industrial 140 bar large size valves (Danfoss).

Major technological results include:

- **Fully integrated, large-scale CO₂ chiller/heat pump:**
 - The system utilizes a factory-assembled, modular concept tailored for flexible field installation. It delivers high-capacity, reversible heating and cooling in one single package, with a combined energy efficiency (COP) between 4 and 6.
- **Development and validation of new large reversible air-source fin-and-tube heat exchanger:**
 - This innovation was essential for meeting project goals.
 - **Reversibility:** For the first time at this scale, a single air-source heat exchanger reliably serves as both the outdoor gas cooler (or condenser) in chiller mode to reject heat to the surroundings and as the evaporator in heat pump mode to harvest energy from the ambient.
 - **Design features:** Includes optimized tube circuitry and large fin spacing, crucial for minimizing frost during heat pump operation and maximizing heat transfer in both running modes i.e. as gas cooler and evaporator.

- **Performance:** Laboratory tests confirmed robust efficiency during the most challenging winter conditions (with effective frost management), and efficient heat rejection during summer operation.
- **Integration:** Its successful operation is a key reason why the system meets its “one-unit-for-all-seasons” design aim.
- **New large-size, high-pressure CO₂ compressors:**
 - Compressors, developed by Bitzer, handled the demands of high-capacity, high-pressure CO₂ cycles.
 - **Reliability and performance:** These compressors demonstrated not just power, but also improved oil management and lower vibration, extending service intervals and lifetime.
 - **Market impact:** The availability of these compressors in the multi-megawatt range makes the system practical for large industry and commercial users, something not achievable with previous compressor technology.
- **Large high-pressure plate heat exchangers:**
 - The project required the design, manufacture, and integration of large plate heat exchangers capable of handling the high transcritical pressures to be able to reach higher water temperatures for the sink side.
 - **Reversibility and robustness:** These plate exchangers were engineered for operation on both the discharge (gas cooler) and suction sides (evaporators) of the cycle, allowing robust operation and low-pressure drop.
 - **Durability:** Validated for repeated pressure cycling and long-term reliability.
- **Industrial-scale CO₂ expanders:**
 - A high-capacity expander was designed, built, and validated to recover work from the expansion step that would otherwise be lost, directly increasing the system COP.
 - **Results:** Both simulation and test data showed great efficiency gains and robust performance, even in highly dynamic field environments.
- **Large industrial CO₂ ejector:**
 - Although the individual ejectors at this scale were not themselves modular, the project team achieved system modularity by deploying three ejectors of two sizes in parallel.
 - **Benefit:** This approach provided flexible capacity control and redundancy, simplifying maintenance and allowing staged operation for optimal performance across varying load conditions.
- **Integration of advanced operational planning tool for heat pump scheduling:**
 - Instead of relying solely on technical component advances, the project developed and implemented an operational planning tool designed to determine the optimal times to run the heat pump. This tool leverages system data on electricity prices, heating and cooling demands, and storage capacity.

- **Functionality and value:** The planning tool intelligently schedules and manages operational setpoints based on forecasted market prices and demand, maximizing cost effectiveness and energy efficiency.
 - **Impact:** By optimally coordinating when the heat pump and storage operate, the system is able to shift energy consumption to periods with lower electricity prices and higher renewable availability, significantly reducing operational costs while ensuring reliably matched supply to varying demand.
 - **Strategic advantage:** This approach to system integration, focused on operational intelligence and planning, is a key reason why the system achieves its “one-unit-for-all-seasons” performance, adapting dynamically between heating and cooling as conditions change, with seamless mode transitions.
- **Extensive performance validation in both lab and field:**
 - All new components underwent detailed laboratory testing and some of the components were proven in an operational industrial setting at Velux.
 - **Outcome:** The system performed to specification under both normal and extreme operating conditions, validating both design and integration choices.

Unexpected technological results and valuable insights:

- **Higher-than-expected part-load and defrost efficiency:** The new reversible air-source fin-and-tube heat exchanger, optimized for both working as a gas cooler and an evaporator, proved extremely effective at handling both heat pump and chiller duties under dynamic real-world loads, including in freezing weather with minimal efficiency loss.
- **Wider application range discovered:** The large reversible air source heat exchanger and the other components developed in the project are now seen as viable solutions for a broader range of industrial and utility applications than initially envisaged – such as district energy and data center cooling.
- **Ejector modularity enhances maintainability and flexibility:** The strategy of installing multiple ejectors provided not only operational resilience but simplified the system’s scalability and future upgrades.
- **Expander efficiency:** The expander demonstrated higher efficiency than anticipated, exceeding initial performance projections. This result not only boosts the system’s overall COP but also paves the way for future industrialization of high-capacity CO₂ expanders in large-scale heating and cooling applications.

The project generated a technology platform that is not only world-leading in its main domain but also adaptable for many future decarbonization projects, thanks to these new large-scale, high-performance, and digitally integrated components.

5.3 Obtained commercial results

The commercial impact of the project has been significant, not only validating the business case and market fit for the new CO₂ reversible chiller/heat pump solution, but also catalyzing partnerships, customer engagement, and new export opportunities.

Highlights of commercial results achieved:

- **Successful demonstration and market reference at Velux:**
 - Although the project originally planned to demonstrate the technology at Arla Foods, unforeseen internal changes meant that Arla was unable to fulfill its role as field demonstration host, ultimately participating only as a “shadow partner.”
 - In response, the consortium undertook an intensive search for a replacement end-user. This effort was successful, and the project was privileged to bring Velux, a well-known Danish industrial group, on board as the new demonstration partner.
 - The successful full-scale installation and demonstration at Velux provided not just essential operational data, but also a credible market reference for further customers, demonstrating reliability and measurable energy and cost savings in a real industrial environment.
- **Acceleration of commercial readiness:**
 - The project moved from laboratory-scale and prototype testing directly to a field-ready, commercially viable product within the time frame of the project.
 - This “real world” track record at Velux enabled consortium partners to build powerful case studies, refine technical documentation, and confidently launch sales activities toward additional industrial and large commercial users.
- **Market interest and early customer dialogues:**
 - The attention generated by the Velux installation and technical publications led to direct inquiries from potential customers in other sectors, including food & beverage, pharmaceuticals, and large commercial buildings.
- **New commercial partnerships and value chain strengthening:**
 - Successful demonstration prompted discussions for new commercial collaborations, both within Denmark and with international stakeholders wishing to replicate the solution for their own applications and markets.
 - Key component suppliers (notably Bitzer, Danfoss, Kelvion, and Güntner) leveraged field performance data in their product portfolios and sales activities, accelerating not just system-level, but also component-level market penetration.
- **Export potential:**
 - The validated solution, now with operational hours at a flagship site in Danish industry, attracted attention from nearby European markets, where similar industrial energy and climate regulations apply.
 - Consortium members began initiating, or were invited to, discussions with partners and clients across Germany, the Netherlands, and other “early adopter” countries.
- **Creation of aftermarket services and digital business opportunities:**
 - The digital twin and IoT-enabled analytics platform developed and tested within this project has been recognized as a valuable product/service in its own right.

- Partners began to offer remote monitoring and performance optimization services, expanding the potential for ongoing revenue streams and deeper customer relationships.

Unexpected commercial results and lessons learned:

- **Resilience and opportunity from partner changes:**
 - While the withdrawal of Arla as a demonstration host initially posed a major risk, the eventual involvement of Velux turned out to be a commercial advantage. Velux's profile, technical engagement, and openness to communication made it an exemplary customer case, and their positive experience provided a strong public endorsement.
- **Faster-than-expected market interest:**
 - Deployment at Velux, combined with dissemination activities, created more immediate and higher-quality leads than expected. The system's lower energy bills, improved operational flexibility, and digital services were especially attractive to customers facing decarbonization and electrification mandates.
- **Expanded market segments:**
 - The fully modular and scalable nature of the technology, proven at Velux, unlocked potential in application areas (data centers, district energy, specialized industrial segments) that were not part of the original commercial focus.

The project achieved commercial validation and early deployment with a high-profile Danish industrial user, created proof points for further customer adoption, and spurred a wave of interest both in Denmark and abroad. The lessons learned and the networks formed, especially in responding flexibly to the change of demonstration host, have left the consortium better positioned and more resilient for scaling the technology across new sectors and markets.

5.4 Target group and added value for users

The project's solutions and component technologies were designed with the needs of several well-defined market segments in mind. Special attention was given to ensure that each type of user and customer benefits directly from the unique technical, operational, and digital features of the system.

Main target groups include:

- **Large industrial companies:**
 - Especially those in the food and beverage sector, pharmaceutical production, and other process industries with simultaneous or seasonally varying requirements for both heating and cooling.
 - These companies face increasing regulatory and cost pressures related to energy use, and many are seeking solutions to phase out fossil-fuel boilers while optimizing energy consumption throughout their production process.
- **Operators of large commercial or public buildings:**
 - This group includes hotels, shopping centers, hospitals, airports, universities, and office complexes, facilities that require reliable and efficient HVAC (heating, ventilation, and air conditioning) with potential for significant energy and cost savings.

- For these users, the reversible CO₂ chiller/heat pump offers a single, modular system capable of meeting space heating, cooling, and often domestic hot water needs throughout the year.
- **District energy and utility companies:**
 - The technology fits as a backbone for district heating and cooling networks, enabling integration of renewable power, electrification of heating, and effective management of system peaks.
- **OEMs, engineering companies, and system integrators:**
 - These companies will benefit from new, proven components, such as large reversible air-source fin-and-tube heat exchangers, large high-pressure plate exchangers, CO₂ ejector packages, expanders, and compressors, for use in custom or proprietary energy systems.

Added value for users in each segment:

- **Reduced capital and operational expenditure:**
 - Combining heating and cooling in one single unit replaces two systems and minimizes both upfront investment and ongoing energy costs.
- **Simpler installation and maintenance:**
 - The modular, factory-built system can be rapidly deployed, reducing downtime and on-site labor. The digital monitoring platform streamlines service scheduling and support.
- **Improved energy efficiency and climate compliance:**
 - With combined COP values of 4-6, users see higher energy efficiency compared with conventional solutions, directly supporting sustainability and decarbonization targets.
 - The use of natural CO₂ (R-744) as refrigerant future-proofs investments, eliminating the regulatory and environmental risks associated with synthetic refrigerants and the flammability associated with hydrocarbons.
- **Enhanced operational reliability and lifetime value:**
 - Advanced operational scheduling, combined with digital monitoring tools, ensures the system is run at optimal times and conditions. This approach helps users avoid unnecessary stress on equipment, minimizes energy costs, and extends system lifetime by aligning operation with demand, electricity prices, and maintenance needs.
- **Flexibility and scalability:**
 - The larger, modular system and new component technologies scale to suit a user's changing needs, whether that means expanding production, retrofitting existing plants, or adapting to new building demands.
- **Strong environmental branding:**
 - Users adopting this technology can document concrete climate and energy savings and communicate leadership in sustainability and innovation.

For each major technology (if sold separately):

- **Large reversible air-source fin-and-tube heat exchangers:**
 - Add value by enabling dual-mode operation with one single outdoor unit, reducing space and capital cost, and boosting year-round efficiency, even in harsh climates.
- **Large high-pressure plate heat exchangers:**
 - Offer robust, reliable performance for both high- and low-pressure CO₂ applications, simplifying system layouts and supporting both flooded and reversible operation.
- **Large modular CO₂ compressors and expanders:**
 - Make it practical to design for higher capacities with fewer, more serviceable machines, increasing reliability and making new business models for service and upgrades possible.
- **CO₂ ejector modules:**
 - By deploying multiple units in parallel, provide operational flexibility and redundancy, enabling staged operation and easier capacity upgrades.

The technology developed in the project creates present-day business value for end-users and system integrators, while also positioning them to meet tomorrow's energy, climate, and digital requirements. The multi-faceted benefits enable the solution to fit into a wide range of industrial, commercial, and utility projects.

5.5 Dissemination of project results

The project team has prioritized a wide and effective dissemination of results, ensuring that the technological advancements, field experiences, and scientific insights reach both professional and public audiences. Dissemination efforts covered the full range from peer-reviewed scientific publishing to industry conferences, trade publications, workshops, online channels, and integration into educational activities.

Key dissemination activities and channels:

- **Peer-reviewed scientific publications:**
 - Project research, especially on advanced CO₂ ejector modeling, component testing, and system performance, has been published in international conference proceedings and scientific journals.
 - Notably:
 - **Kanbur, B.B., Busch, A., Kriezi, E.E., Markussen, W.B., Kærn, M.R., Kristófersson, J., Walther, J.H. (2023).** "Computational multiphase mixture simulations of a two-phase R-744 ejector geometry in transcritical R-744 heat pump applications." *Proceedings of the 14th International Conference on Computational Heat and Mass Transfer (ICCHMT23), Düsseldorf.*
 - Detailed study of two-phase CO₂ ejector behaviors using advanced CFD, validating and improving simulation approaches for FORCO2's core technology.
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 - Presents advanced CFD (TPTE model) simulations of two-phase CO₂ ejector geometries, with validation against experimental data, supporting performance optimization for the FORCO2 heat pump and refrigeration systems.
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 - Compares two advanced CFD mixture models (STAR-CCM+ TPTE and ANSYS CFX EPCM) for predicting the behavior and performance of two-phase CO₂ ejectors over subcritical and supercritical conditions, validating simulation accuracy with experimental data to support the design and optimization of the FORCO2 heat pump systems.
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 - Develops and validates an open-source Eulerian-Eulerian two-fluid CFD model in OpenFOAM for two-phase CO₂ ejectors, achieving high accuracy for motive flow prediction and improving suction flow modeling for FORCO2-related applications.
- **Kanbur, B.B., Busch, A., Kriezi, E.E., Markussen, W.B., Kærn, M.R., Kristófersson, J., Walther, J.H. (2025).**
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 International Journal of Numerical Methods for Heat & Fluid Flow, Vol. 35, No. 6, pp. 2004–2024. DOI: 10.1108/HFF-01-2024-0006
 - Presents a new multiphase mixture CFD methodology with a custom thermodynamic look-up table for two-phase CO₂ ejectors in heat pumps, reporting accuracy through comparison with experiments and enabling further digital optimization in the FORCO2 system development.

- **Kriezi, E.E., Kanbur, B.B., Markussen, W.B. (2024).** "Thermodynamic modelling of two-phase R-744 ejectors in R-744 heat pumps." 16th IIR Gustav Lorentzen Conference on Natural Refrigerants, College Park, Maryland, USA, 2024. DOI: 10.18462/iir.gl2024.1173
 - Presents and validates a thermodynamic model for R-744 ejectors using both local and predicted local coefficient approaches, achieving accurate predictions of pressure and motive mass flow rates, and advancing neural network-based ejector modeling for the FORCO2 heat pump applications.
- **Kanbur, B.B., Markussen, W.B., Busch, A., Kriezi, E.E., Kærn, M.R., Kristófersson, J., Walther, J.H. (2023).** "Computational fluid dynamics simulations of a two-phase R-744 ejector geometry in expansion processes of vapor-compression refrigeration systems." 26th IIR International Congress of Refrigeration (ICR2023), Paris, France, 2023. DOI: 10.18462/iir.icr.2023.0480
 - Presents CFD simulations using a multiphase mixture model for two-phase R-744 ejectors under transcritical expansion, evaluating pressure, temperature, mass fraction, Mach number, and mass entrainment ratio against experimental data to support ejector optimization in the FORCO2 systems.
- **Delêtre, P.-J., Kristófersson, J., Latvenas, A., Kristoffersen, J.W., Andersen, H., Christensen, K.G. (2024).** "Novel large scale combined heating and cooling CO₂ system." 16th IIR Gustav Lorentzen Conference on Natural Refrigerants, College Park, USA.
 - Presents the design, operational modes, and experimental validation of the reversible 1500 kW prototype developed in FORCO2, including test results and comparisons to traditional systems.
- **Javerschek, O., Silva, A., Boscan, M. (2024).** "R744 heat pumps with ejectors: projects, objectives and results." *IIR Compressors Conference, Slovakia.*
 - Provides a compressor and ejector manufacturer's perspective, reports development and field results from FORCO2, and discusses industrial-scale R744 system performance and challenges.
- **Sadi, M., Arabkoohsar, A. (2025).** "Optimization of Industrial Heat Pump Operations Using Innovative Strategies and Thermal Energy Storage Integration." *Journal of Energy Storage* (accepted/in press).
 - Applies operational planning and AI-based optimization to the FORCO2 system, showing substantial potential for operational cost reduction and efficiency improvements by integrating storage and advanced control strategies.
- **Sadi, M., Arabkoohsar, A. (2025).** "The Role of Demand Profile in Optimizing Operational Planning." Proceedings of the 10th World Congress on Momentum, Heat and Mass Transfer (MHMT 2025), Barcelona, Spain, April 2025. Paper No. ENFHT 170.
 - Investigates how different heat demand profiles influence operational costs for heat pump systems with storage, employing a genetic algorithm for cost

optimization and showing that extremely low demand profiles offer the greatest savings potential.

- **Industry conferences and professional events:**

- Results, use cases, and technical lessons were presented at leading European and international conferences, including:
 - 14th International Conference on Computational Heat and Mass Transfer (IC-CHMT23), Düsseldorf, Germany.
 - 10th IIR Conference: Ammonia and CO₂ Refrigeration Technologies, Ohrid, North Macedonia.
 - 16th IIR Gustav Lorentzen Conference on Natural Refrigerants, College Park, Maryland, USA.
 - IIR Compressors Conference, Slovakia.
 - 26th IIR International Congress of Refrigeration (ICR2023), Paris, France.
 - 10th World Congress on Momentum, Heat and Mass Transfer (MHMT 2025), Barcelona, Spain.
 - Chillventa Trade Show (Nuremberg, Germany) – industry technology presentation and outreach.
 - Refrigeration and Heat Pump Forum (Denmark) – major Danish event for refrigeration and heat pump innovation, industry, and research exchange.
 - Other international and national workshops, symposia, and innovation forums as referenced by the project.
- Multiple partners have taken part in invited presentations, panel debates, and technical workshops tailored for both end users and technology developers.

- **Technical and trade publications:**

- Project-authored journal articles from the FORCO2 project have been published in leading international journals, including:
 - Applied Thermal Engineering – research on modeling, simulation, and optimization of heat pump and ejector technology.
 - International Journal of Numerical Methods for Heat & Fluid Flow – advanced computational and numerical methods applied to multiphase flow and ejector simulation.
 - Journal of Energy Storage – operational planning, optimization, and integration of energy storage with heat pump systems.
- Technical briefs and “lessons learned” summaries have been prepared and distributed through partner networks to reach system designers, facility managers, energy consultants, and procurement specialists.

- **Education and training activities:**

- Findings and case material have been incorporated into courses at DTU (Technical University of Denmark) and into professional training programs at Danish Technological Institute (DTI), providing future engineers, technicians, and specialists with state-of-the-art knowledge in CO₂ refrigeration and heat pump technology.

- **Direct stakeholder engagement:**

- The team has offered targeted workshops for potential users, held meetings with policy makers, and contributed to the formation of new sector standards, further supporting the technology's adoption at scale.

The project's dissemination has been extensive, international, and multi-faceted, ensuring that new knowledge, field-tested solutions, and practical guidance reach all relevant segments, from scientific peers, industry professionals, and technology buyers to students and policy decision-makers. This broad outreach is already supporting market uptake, technology replication, and continued innovation in the field of industrial-scale CO₂ refrigeration and heat pump systems.

6. Utilisation of project results

6.1 Utilization of technological results

The technological achievements from this project have laid a strong foundation for widespread impact across multiple sectors, as well as future innovation and continued value creation within the project consortium and beyond.

How the results will be utilized:

- **Industrial and commercial deployment:**

- The validated large-scale CO₂ chiller/heat pump system and its components will be further rolled out by manufacturers and system integrators, including partners such as Fenagy, Bitzer, Danfoss, Kelvion, and Güntner, across Denmark and internationally.
- Building on proven success at Velux, similar solutions will be implemented in food processing, pharmaceuticals, large commercial buildings, district energy networks, data centers, and other sectors seeking efficient, sustainable heating and cooling.

- **Wider adoption of advanced components:**

- The new large reversible air-source fin-and-tube heat exchanger, large size high-pressure plate heat exchangers, high-capacity compressors, expanders, large size ejectors, and industrial large size refrigeration valves will be manufactured and integrated into both standard offerings and custom engineering projects.
- OEMs and system designers can adopt these field-proven components to create more efficient, scalable, and flexible energy systems, lowering risk and accelerating their own product development.

- **Integration and improvement of digital solutions:**
 - The digital twin, IoT cloud analytics, and predictive maintenance platform developed in the project will become a standard service offering new installations and can also be retrofitted to existing systems.
 - Digitalization partners within the project will enhance their IoT platforms based on lessons learned, offering new monitoring, optimization, and remote service solutions to a wider client base.
- **Education and researcher uptake:**
 - Research institutions such as DTU and DTI will continue to use the project's technological results as real-world case studies and demonstration material in engineering courses, professional training, and further research.
 - The validated simulation models, datasets, and test results will serve as benchmarks for ongoing academic work in refrigeration, heat pump technology, and sustainable industrial energy systems.
- **Standardization and sector influence:**
 - Insights from the project, including design best practices, digital monitoring approaches, and component performance data, will influence industry standards and sector guidelines for CO₂-based and hybrid heating/cooling systems.
 - Key partners are expected to participate in standard-setting bodies and technical committees using knowledge generated from the project.

Who will utilize the results:

- **Industrial technologists and system integrators** will lead new installations and retrofits of the developed technology, both as packaged units and as customized solutions.
- **Heat pump manufacturers** (Fenagy) will use the validated system concept, advanced components, and digital capabilities to expand their product lines and offer new solutions targeted at both domestic and export markets.
- **Component manufacturers** (Danfoss, Bitzer, Kelvion, Güntner) will leverage the new designs to improve their global product ranges, support service enhancements, and open new market channels.
- **DTI (Danish Technological Institute)** will use the project's technological results and data to provide independent testing, certification, and technical guidance to industry, in Denmark and internationally, while also supporting further industry-driven R&D projects.
- **Universities and training institutes** will use the project outcomes to train the next generation of engineers, technicians, and energy professionals, embedding knowledge throughout the wider industry.
- **Consulting engineers and sector advisors** will use project data and documentation to support best-practice guidance, investment decisions, and strategic planning for clients seeking efficient, future-proof heating and cooling.

The technological results of the project are positioned for substantial and sustainable impact, enabling both immediate applications and ongoing innovation for years to come.

6.2 Utilization of commercial results

The commercial achievements of the project have laid the groundwork for widespread market adoption, business growth, and job creation across the value chain, from system builders to component suppliers.

How the commercial results will be utilized and by whom:

- **Market rollout by system manufacturers and integrators:**
 - The field-validated CO₂ chiller/heat pump solution will be commercialized primarily by heat pump manufacturer (Fenagy), and system integrators who will incorporate the technology into new installations in industry and large buildings.
 - Demonstration at Velux provides a high-profile, credible reference site that enables more confident marketing and faster adoption by both Danish and international customers.
- **Component commercialization:**
 - Project partners such as Bitzer, Danfoss, Kelvion, and Güntner will incorporate the new large-scale compressors, ejectors, and heat exchangers into their standard and custom product portfolios.
 - These components, having been proven in real-world operation, will now be marketed not only for full CO₂ systems, but also as upgrade solutions for existing equipment in need of efficiency improvement or regulatory compliance.
- **Expansion of digital services:**
 - The IoT cloud platform and digital twin analytics developed during the project will be commercialized to support advanced operation planning and proactive maintenance. These digital services will enable remote monitoring, data-driven optimization of system operation schedules, and predictive maintenance planning to maximize system uptime and efficiency. By integrating automated diagnostics and smart control algorithms, customers will be empowered to make informed operational decisions and address maintenance needs before they develop into costly outages, supporting new, recurring business models built on performance and reliability.
- **Strengthening of the sales network and export activities:**
 - The project's outcome is already being leveraged in marketing campaigns, sales presentations, technical briefs, and at international trade shows, enabling project partners to establish themselves as leaders in advanced CO₂-based climate solutions.
 - Completed demonstrations open doors for export to countries across Northern and Western Europe, where there is a strong drive for electrification and sustainability in industrial and commercial energy systems.

Impact on turnover, exports, employment, and investments:

- **Turnover and export growth (so far and expected):**
 - The project's demonstration phase already led to increased turnover for several partners, as demonstration results generated new sales leads, case references, and direct product orders.

- The international interest and strong reference from Velux have positioned the partners well for a continued increase in exports, especially to “early adopter” markets with ambitious climate policies.
- Partners anticipate a year-on-year revenue increase from both system sales and components, with Fenagy, Bitzer, Danfoss, Kelvion, and Güntner all expecting significantly higher market share and export volume.
- **Employment:**
 - As commercialization begins, partners have reported and continue to expect new hiring in engineering, manufacturing, digital services, sales, and field service roles.
 - The expansion of production capacity, especially for large-scale heat pumps, advanced controls, and custom heat exchangers, will require additional skilled labor and support staff.
- **Private investment and ongoing development:**
 - The proof of market, technical, and user acceptance delivered by the project has encouraged further private investment, both for scale-up of manufacturing and for continued R&D in product optimization, digital tools, and regional market adaptation.
 - New collaborations and joint ventures are being explored, further catalyzed by the market validation, to capture new business models in digital energy management and smart service offerings.

The commercial results of the project are being rapidly harnessed by both system manufacturers and component suppliers for direct market rollout. Strong references, new business models, and an expanding network of international export opportunities point to ongoing increases in turnover, exports, employment, and private investment, reinforcing the project’s contribution to green industry growth both in Denmark and abroad.

6.3 Competitive situation in the market

A key contextual factor is that the sanctions on Russian gas in Europe have been a vital driver in accelerating the move away from fossil fuels and towards more environmentally sustainable solutions. This has increased the urgency and attractiveness of alternatives that reduce dependence on fossil-based energy, such as advanced CO₂-based heating and cooling systems.

The market for large-scale heating and cooling is rapidly evolving under the twin pressures of climate policy and energy cost volatility. The project’s CO₂-based reversible chiller/heat pump solution enters a marketplace traditionally dominated by well-established but less sustainable technologies, and where only a handful of new entrants offer comparable efficiency or environmental benefits.

Competitive landscape and existing solutions:

- **Conventional systems (majority of installed base):**
 - Most industrial and large commercial facilities currently rely on a combination of separate solutions for heating (typically gas or oil boilers, or in some cases, traditional heat pumps) and cooling (conventional chillers based on HFC/HFO, ammonia or CO₂ refrigerants).

- These systems are easy to source from multinational brands but involve a relatively low combined COP and in many cases rely on refrigerants that are rapidly becoming obsolete due to environmental regulation.
- **High-efficiency heat pumps with synthetic refrigerants:**
 - Several large OEMs offer advanced heat pump systems using HFC, HFO, or blends (e.g., R410A, R134a, R1234ze). Brands include Daikin, Trane, and Johnson Controls.
 - While some can achieve good efficiency, these systems are vulnerable to upcoming bans, taxes, or restrictions on F-gases, and do not provide integrated reversible (heating+cooling) solutions at the same industrial scale.
 - Most synthetic refrigerants present not only a global warming problem (due to their high or moderate GWP) but also contribute to environmental pollution through PFAS substances, such as trifluoroacetic acid (TFA), which are extremely persistent in the environment. Regulatory focus on both their climate and PFAS impacts is increasing.
- **Natural refrigerant systems (ammonia, propane):**
 - Companies like GEA and Mayekawa have advanced ammonia systems for industrial use, and several niche suppliers offer propane (R290) heat pump packages. However, ammonia's toxicity and regulatory requirements and propane's flammability often limit market acceptance, especially for applications in densely populated or public environments.
 - Most ammonia and propane systems are still designed primarily as heat pumps, not as fully reversible combined heating/cooling packages.
- **Emerging CO₂-based solutions:**
 - A very limited number of suppliers (notably Advansor, Feangy, Dorin, and to some others) have begun marketing CO₂-based heat pumps for industrial and commercial applications, with a handful of reversible prototypes appearing in recent years.
 - Most of these are smaller in scale (hundreds of kW, compared to this project's multi-megawatt offering), optimized for specific supermarket or commercial building niches, or lack the advanced digital twin/IoT integration and robust field references demonstrated by this project.

Competitive advantages of the project solution:

- The developed CO₂-based reversible system uniquely combines:
 - Use of a natural, climate-safe, future proof refrigerant.
 - High-efficiency operation in both heating and cooling modes, with seamless reversibility at multi-megawatt scale.
 - Proven operation in harsh climates (robust defrost, anti-frost, and oil management by design).
 - Modular and scalable installation model.
 - Full IoT/digital cloud integration, delivering ongoing optimization and predictive maintenance.
 - Clear field track record at a high-profile industrial user (Velux).

Although the market includes several established heating and cooling providers, none of them currently offer a directly comparable package of natural refrigerant, large-scale, true reversibility, digital integration, and documented energy and climate performance as demonstrated in this project. The project partners are therefore well positioned for early-mover advantage in a growing, policy-driven market segment

6.4 Entry and sales barriers, and how they are expected to be overcome

Bringing a novel, large-scale CO₂ reversible chiller/heat pump system to the market is not without its challenges. Several entry or sales barriers exist in the industrial energy and HVAC sectors, but the project and its consortium have developed a variety of strategies to address to overcome these barriers.

Identified entry and sales barriers:

- **Customer conservatism and risk aversion:**
 - Many industrial and commercial energy users are hesitant to adopt new technologies for mission-critical heating and cooling applications. The perceived risk of operational disruption, the unfamiliarity with CO₂ technology, and reliance on established vendors can slow decision-making and investment in innovative systems.
- **Lack of market awareness and references:**
 - Large clients often require proven, real-world references before investing in new system types, especially at the multi-megawatt scale. Prior to this project, there were few, if any, local examples of CO₂-based integrated heating and cooling at scale.
- **Integration complexity and skills shortage:**
 - The industry often lacks experience with CO₂ systems, particularly when it comes to installation, commissioning, and service. Designing for safe, efficient operation, including understanding high-pressure handling and digital twin controls, requires upskilling of contractors and engineers.
- **Higher initial investment cost compared to traditional systems:**
 - First-of-kind solutions can carry a higher up-front capital cost, especially when supply chains are not yet scaled, and customers focus on short payback periods rather than life-cycle savings.
- **Service network and spare parts availability:**
 - Customers expect robust after-sales support, rapid supply of spare parts, and local service competence, which is often challenging for new technologies or smaller manufacturers.

How these barriers are expected to be overcome:

- **Demonstration and reference sites:**
 - The full-scale installation and successful operation at Velux have provided a credible, high-profile market reference, materially reducing perceived technological risk for new customers and enabling direct site visits, case studies, and proof of concept.

- **Partnering with recognized market leaders:**
 - The involvement of well-known component and system suppliers (Fenagy, Bitzer, Danfoss, Kelvion, Güntner, ElCon) reassures customers about product quality, reliability, and continuity of technical support. Notably, Fenagy is part of Beijer Ref, the world's largest wholesale group for refrigeration equipment. This relationship gives Fenagy a powerful channel to market the developed solution, leveraging Beijer Ref's extensive distribution and customer network both in Denmark and internationally.
- **Comprehensive training and support:**
 - Consortium partners continue to invest in training installers, service personnel, and engineers, offering workshops, professional courses (in partnership with DTI), as well as commissioning and after-sales support packages.
- **Improved customer communication and digital transparency:**
 - The remote monitoring, operational planning, and performance analytics developed in the project offer unprecedented transparency and operational insight, building customer trust and lowering barriers to adoption by de-risking system performance and service.
- **Flexible financing models and TCO (Total Cost of Ownership) communication:**
 - By documenting and communicating the superior life-cycle cost (TCO) and full value proposition, and, where appropriate, partnering with financial service providers to offer leasing or shared savings schemes, the higher initial investment can be offset and justified against future savings.
- **Scalable modular design and local support:**
 - The modular, factory-built system approach simplifies on-site installation and commissioning, making it easier for new markets to scale up without undue complexity or risk.

Entry and sales barriers are real, but by combining strong demonstration references, expert value chain partners, comprehensive training, digital transparency, and a strong focus on delivering service and value throughout the system lifetime, the consortium is well positioned to accelerate market adoption and reduce obstacles for future customers.

6.5 Contribution to energy policy objectives

The project's results make a direct and substantial contribution to achieving national and European energy and climate policy objectives. By connecting innovative technology, commercial deployment, and practical field experience, the new CO₂-based reversible chiller/heat pump system addresses several critical policy targets.

Keyways the project supports energy policy objectives:

- **Accelerating the phase-out of fossil fuels:**
 - The project enables industrial companies, large buildings, and district energy systems to replace fossil-fuel-based boilers with a high-efficiency, electrically driven alternative.

- By harvesting both heating and cooling from a single system, the overall energy demand drops dramatically, and the direct consumption of oil, gas, or coal for process and building heat can be sharply reduced or eliminated.
- **Leveraging Danish and European green electricity:**
 - The solution uses electricity, much of it produced from wind, solar, or other renewables, instead of burning fossil fuels. This directly boosts the share of renewables in the final energy demand and supports integration of variable renewables into the energy system.
- **Advancing electrification and sector integration:**
 - The technology helps align industrial, commercial, and building processes with the overall transition to electrified, flexible energy demand, enabling better sector coupling and a more resilient energy system.
- **Delivering major energy efficiency gains:**
 - With a combined system COP of 4-6, the solution uses 4-6 times less primary energy per delivered unit of heat/cooling compared to direct electrical resistance heating or separate conventional chiller and boiler systems.
 - This efficiency improvement not only lowers bills for users but reduces peak loads and the need for new grid or generation capacity, easing pressure on the wider energy system.
- **Reducing greenhouse gas emissions:**
 - The project offers a pathway for large-scale, measured GHG emissions reductions. For Denmark alone, full-scale implementation of the technology could reduce CO₂ emissions by more than 2 million tons annually by 2041.
 - The use of the natural refrigerant CO₂ (R-744) eliminates direct emissions otherwise associated with synthetic (high-GWP) refrigerants, supporting both F-gas regulation compliance and long-term environmental goals.
- **Supporting policy targets for energy security and independence:**
 - By reducing dependence on imported fossil fuels and using locally generated renewables, the project strengthens security of supply and enhances Danish and European energy independence, as articulated in official energy strategies.
- **Alignment with Danish and EU frameworks:**
 - The project supports the Danish ambition of a 70% CO₂ reduction by 2030 (relative to 1990) and provides practical tools for reaching the EU's targets of climate neutrality by 2050.
 - Features such as cloud-based monitoring and digital documentation also enable high-quality ESG reporting and ease of regulatory compliance for adopters.

Broader policy impact:

In addition to its technical and climate contributions, the project has shown the unique value of Danish and European collaborative innovation in real-world decarbonization. By developing and field-validating solutions at industrial scale and exporting both products and know-how, the results help position Denmark and its partner companies as leaders and reference points for the ongoing global green energy transition.

The project results are a powerful enabler for the realization of energy policy, showing how front-edge technology, full value chain involvement, and real-market deployment can combine to deliver cleaner, smarter, more efficient, and more competitive energy outcomes for society.

7. Project conclusion and perspective

The project has successfully demonstrated that large-scale, reversible CO₂-based chiller and heat pump systems represent a technically and commercially viable solution for the decarbonization of industrial, commercial, and public-sector energy systems. Through the combined efforts of technology development, advanced component engineering, digital integration, and real-world demonstration, the consortium achieved all main objectives:

- A fully functional, market-ready factory-built system was designed, installed, and validated at scale, delivering both heating and cooling with a combined COP far exceeding conventional solutions.
- Core innovations, including the large reversible air-source fin-and-tube heat exchanger, modular high-pressure compressors, plate exchangers, industrial ejectors, expanders, and digital monitoring, proved effective, robust, and adaptable for diverse end-user needs.
- The technology platform now enables measurable reductions in fossil fuel use, energy costs, and greenhouse gas emissions, contributing directly to climate, competitiveness, and sustainability goals.
- The project established strong new partnerships across the value chain, strengthened Danish and European industry leadership, and provided a commercial reference for future projects.
- Digital tools, such as IoT platforms and advanced operation planning, unlocked ongoing efficiency gains and positioned users for continuous improvement over the system's operational life.

In conclusion, the project has laid the groundwork for large-scale market adoption of climate-friendly, digitally optimized industrial heat pump and chiller solutions, setting a new standard for efficiency, reliability, and sustainability in the sector.

The project's successful demonstration of a large-scale, reversible CO₂-based chiller and heat pump system opens several key pathways for further development, deployment, and market growth. The next steps are designed to ensure broader adoption, increased impact, and ongoing technological leadership.

Planned and anticipated next steps include:

- **Wider market rollout:**
 - The validated solution and components will be launched commercially by project partners and industry stakeholders, with focused marketing towards industrial clients, large commercial buildings, and district energy providers.
 - Experience and performance data from the Velux demonstration will be used to build customer confidence and accelerate adoption, with new installations already being planned or negotiated in Denmark and across Europe.

- **Scaling of manufacturing and supply chain:**
 - Manufacturing partners will ramp up production of key components, including large reversible air-source heat exchangers, high-pressure plate exchangers, compressors, expanders, and modular ejectors, to meet anticipated demand for multi-megawatt systems.
 - Efforts will be made to further optimize costs and streamline delivery, leveraging lessons learned from the prototype and initial field units.
- **Continuous improvement based on operational feedback:**
 - Data from deployed units will be leveraged through the IoT platform and advanced operation planning to refine control algorithms, optimize set-points, and quickly detect new opportunities for enhancing both efficiency and reliability.
 - Feedback from new customer environments will support continuous product and service innovation.
- **Expansion of digital services and training:**
 - The digital monitoring, analytics, and predictive maintenance services tested in the project will be further commercialized, offered both as standard features for new systems and as upgrades/retrofits for existing customers.
 - Comprehensive installer, operator, and service engineer training programs will be expanded, in partnership with technical institutes and industry associations, to build a robust ecosystem of expertise.
- **Exploration of new market segments and geographies:**
 - Partners will explore new applications for the technology and adapt system configurations to serve a wider range of needs.
 - Collaboration and exports to early-adopter regions (such as Germany, the Netherlands, and Scandinavia) will be prioritized.
- **Contribution to standards and policy development:**
 - Project results and best practices will be shared in relevant standardization bodies, technical committees, and policy forums, helping shape supportive regulatory and market frameworks for CO₂-based heating and cooling.
- **Ongoing research and innovation:**
 - Research partners will use the validated system, component breakthroughs, and extensive performance data as a platform for new R&D initiatives, addressing future efficiency gains, integration with renewables and energy storage, and pushing the boundaries for natural refrigerant systems.

The next steps for the developed technology focus on translating project successes into wide-scale deployment, robust support services, continuous technological advancement, and an active contribution to the sustainable transformation of industrial and commercial energy systems in Denmark and internationally.

8. Appendices

- Add link to relevant documents, publications, home pages etc.