DEVELOPMENT OF NEXT GENERATION LARGE-SCALE HEAT PUMP SYSTEMS (NEXTHEPS)

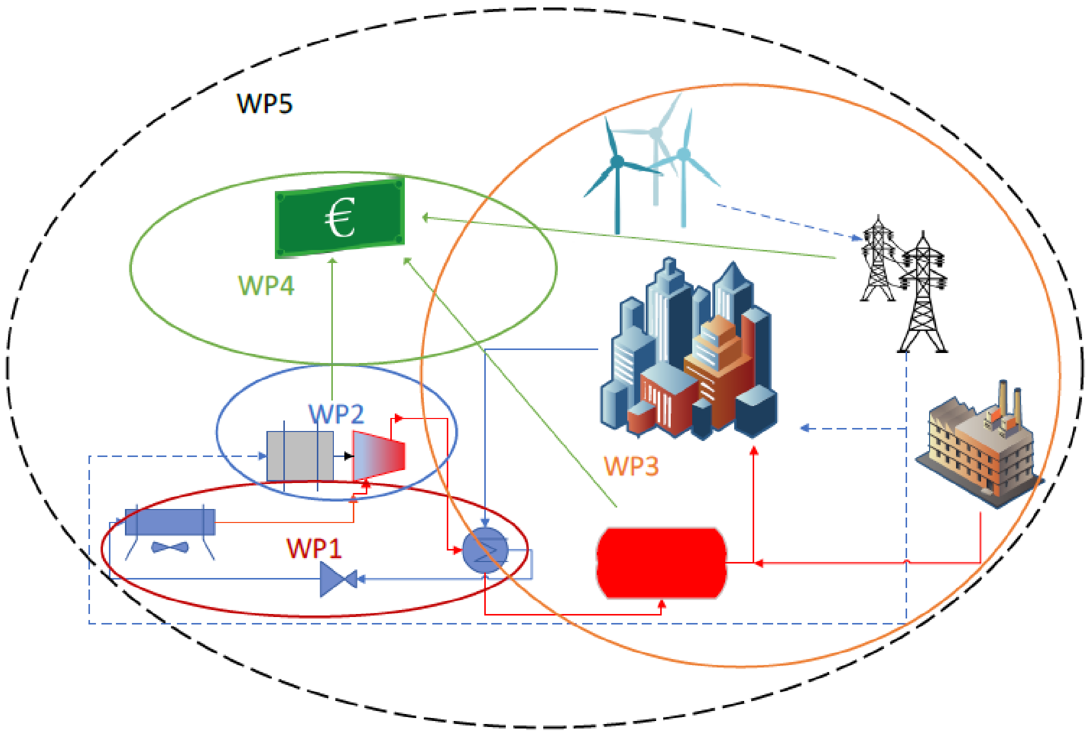
SUMMARY OF THE PUBLIC RESEARCH PROJECT

NEXTHEPS: Project general information

- Research project on large-scale high temperature heat pumps
- Project duration 9/2022-4/2025
- Funded by Business Finland
- Project partners:
  - LUT University
  - The Switch
  - Vahterus
  - Fincoil LU-VE
  - Suomen tekojää
  - Nevel
  - Suur-Savon Sähkö
  - Finnish heat pump association (SULPU).

NEXTHEPS: project work package structure

- WP 1: Heat Transfer, fluid dynamics and thermal properties of heat transfer fluids
- WP 2: High-speed turbo compressor and electrical motor development to create a hermetic high-power component for future heat-pump systems
- WP 3: Heat pump process integration and optimisation, energy system modelling
- WP 4: Market needs and new business models for heating solutions
- WP 5: Coordination, national and international networking



NEXTHEPS: key research questions

- 1. What are optimal heat collector designs and heat transfer fluids for large scale heat pumps in different operation environments?
- 2. What are main design principles for next generation high-speed high-power heat pump turbocompressors?
- 3. How large-scale heat pump system is dimensioned and integrated to district heating or industrial process heating systems?
- 4. What are the future business models and market mechanisms through which technology providers, utility companies and energy service providers can enter to heat pump markets?
- 5. How Finnish heat pump provider ecosystem can be strengthened (National SWOT analysis of Finnish heat pump actors), who are key international partners and networks to enter to the heat pump markets?

WP 1: Heat Transfer, fluid dynamics and thermal properties of heat transfer fluids

WP 1: Design of heat collector and heat delivery processes

- The research focus is on investigating the working fluid for high-temperature and high-speed heat pumps.
- The heat pump in this project is designed for district heating, utilising air as the heat source.
- The main heat exchangers of the heat pump are thermally designed, and the influence of the working fluid on the heat exchanger design is examined.
- The thermal design of the air-source heat collector field and its frosting are investigated.

Objectives and goals

- Select a suitable working fluid for a high-temperature and high-speed heat pump.
- Understand how working fluid influences the thermal design of the main heat exchangers of the heat pump.
- Create a thermal design of the heat collector field and understand how the design of the field and ambient conditions influence the operation of the field.

Task 1.1: Description and objectives

- The task focuses on identifying suitable working fluids for high-temperature and high-speed heat pumps.
- Based on the comparison of working fluids based on their physical properties, future legislation and process simulation, a working fluid for the project is selected.
- The working fluid used for the heat pump design is pentane.

Objective

- Select the working fluid for the heat pump design.
- Identify suitable working fluids for high-temperature and high-speed heat pumps.

Task 1.1: Working fluids

- Working fluid properties were reviewed, and based on this review, suitable working fluids for high-temperature and high-speed heat pumps were identified.
- The focus of the project is on low global warming potential (GWP) fluids.
- Based on the review of possible future legislation, the focus was directed towards natural working fluids suitable for high-temperature and high-speed heat pumps.

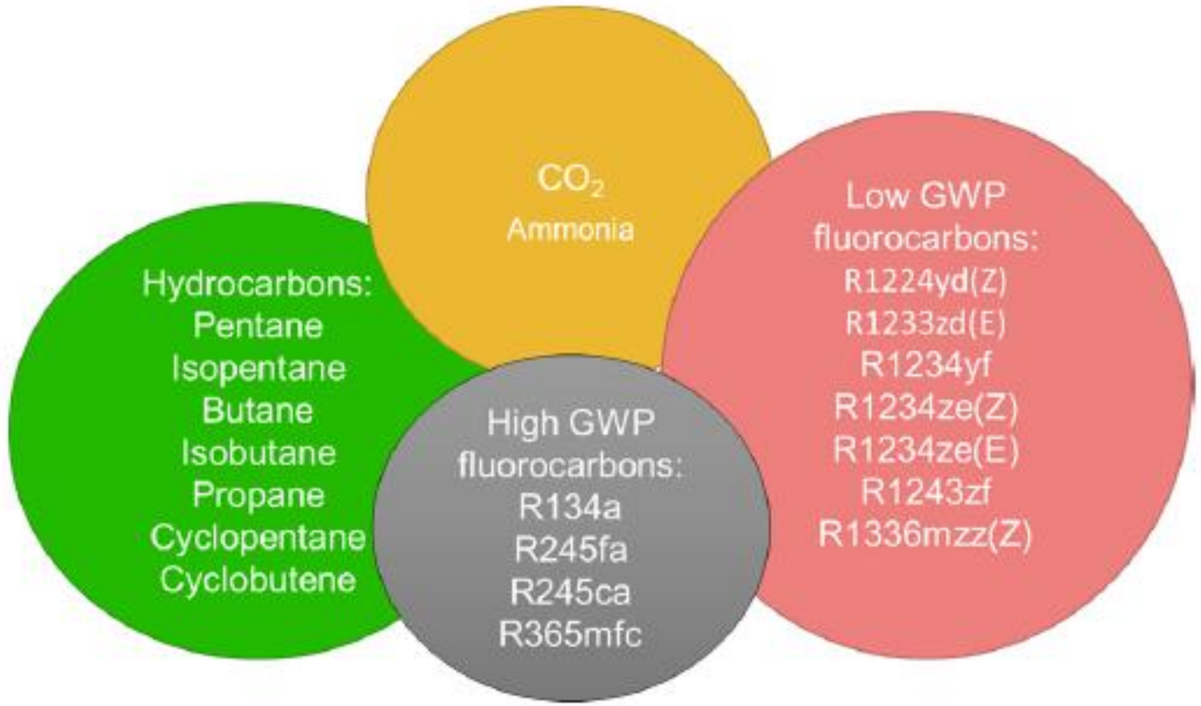


Figure 2.2: Categorization of the investigated fluids.

Task 1.1: Heat pump cycle

- Preliminary investigation of the influence of working fluid on heat pump cycle and compressor design was conducted.
- The two-stage design with a flash intercooler was selected for further investigation.

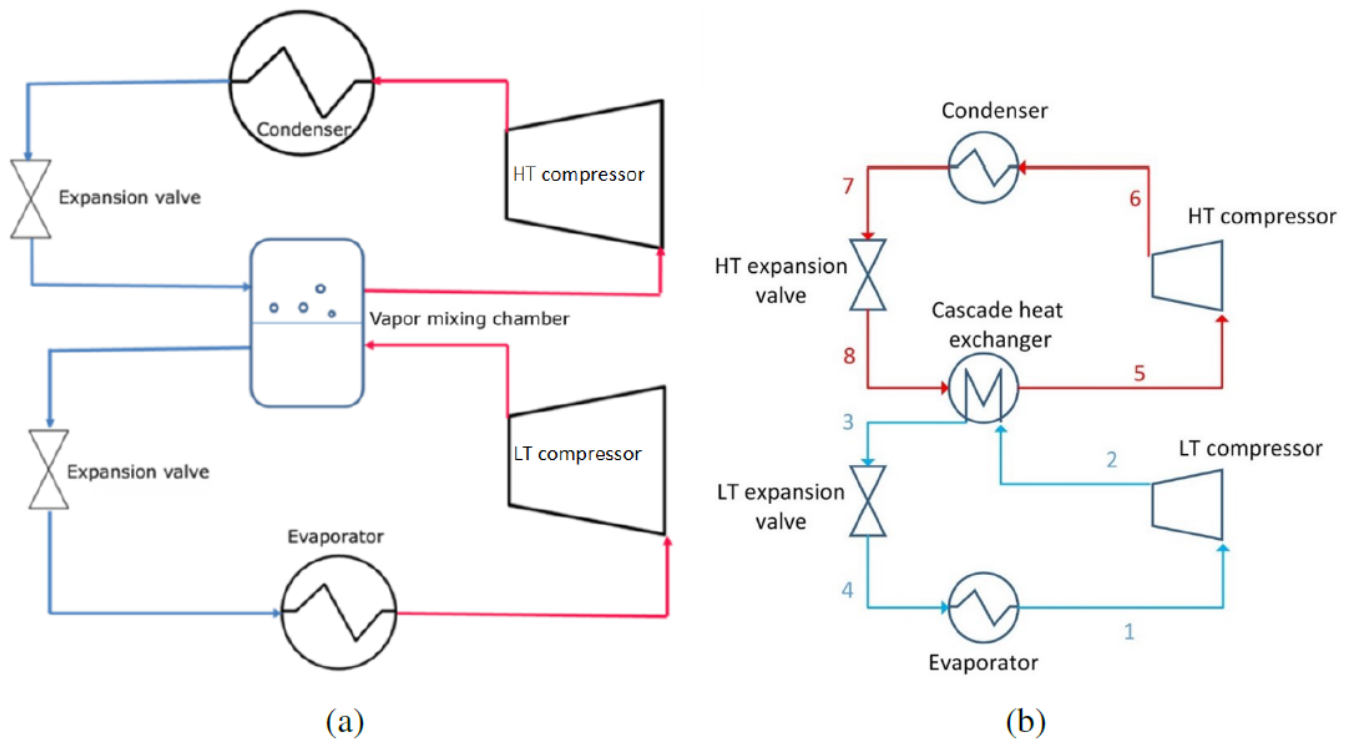
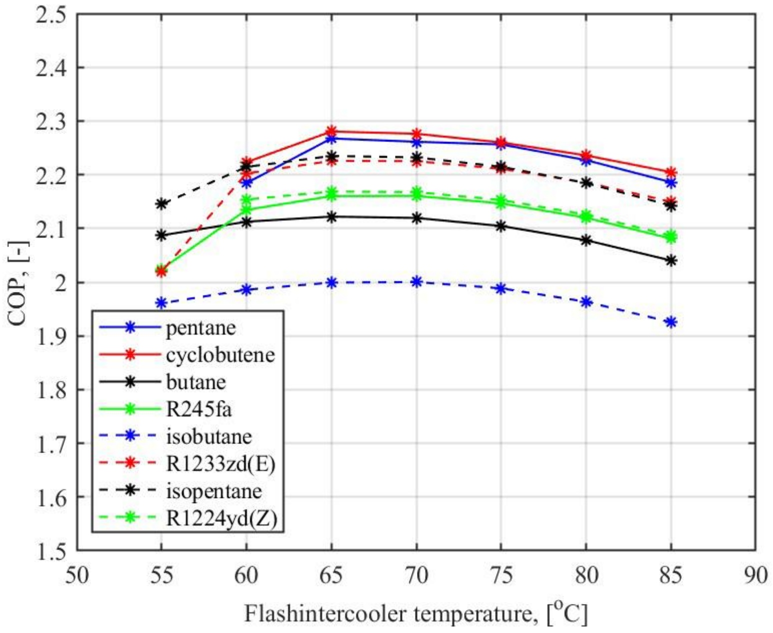
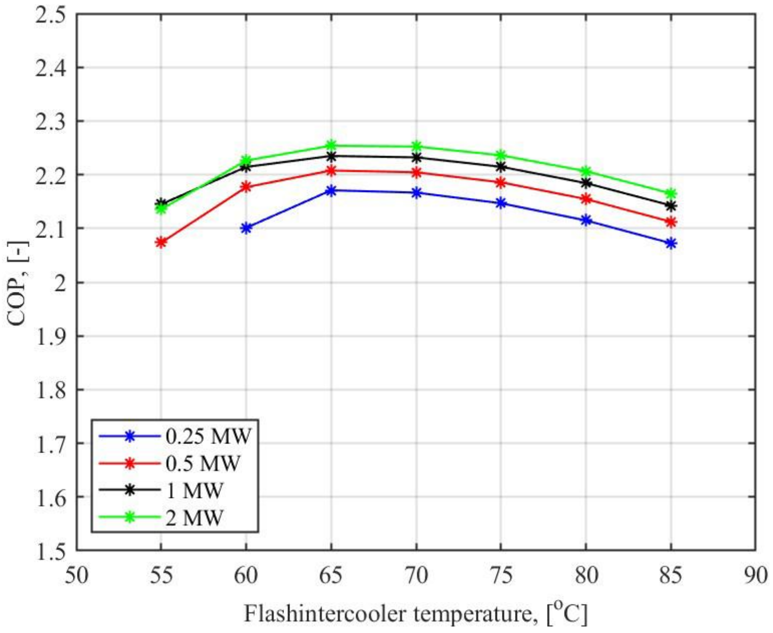


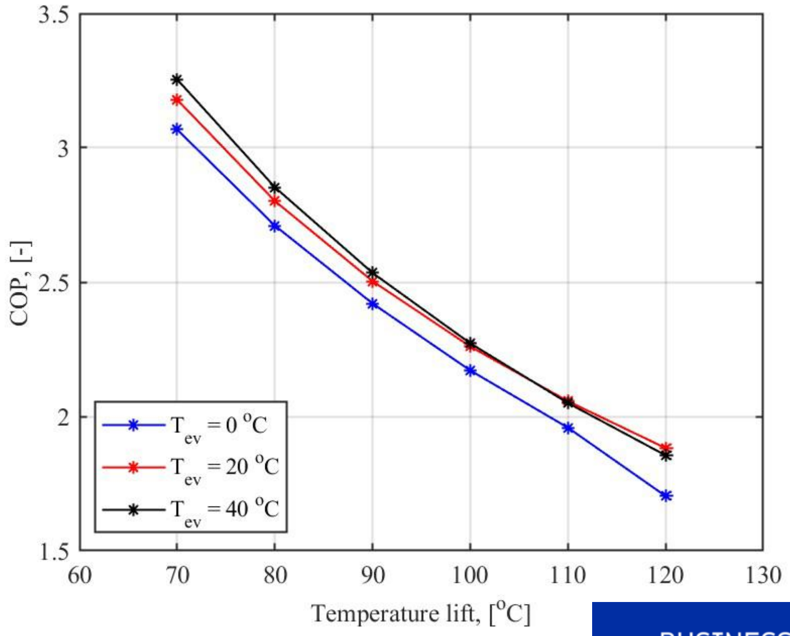
Figure 4.1: (a) Two stage process with a flash intercooler. Same refrigerant circulates in both LT and HT cycle. (b) Two stage heat pump with a cascade heat exchanger. Different fluids can be used in LT and HT cycle.

Task 1.1: Process simulations

- Process simulations were conducted to investigate how the coefficient of performance (COP) is affected by the selection of working fluid.
- Pentane was found to be one of the most effective working fluids.







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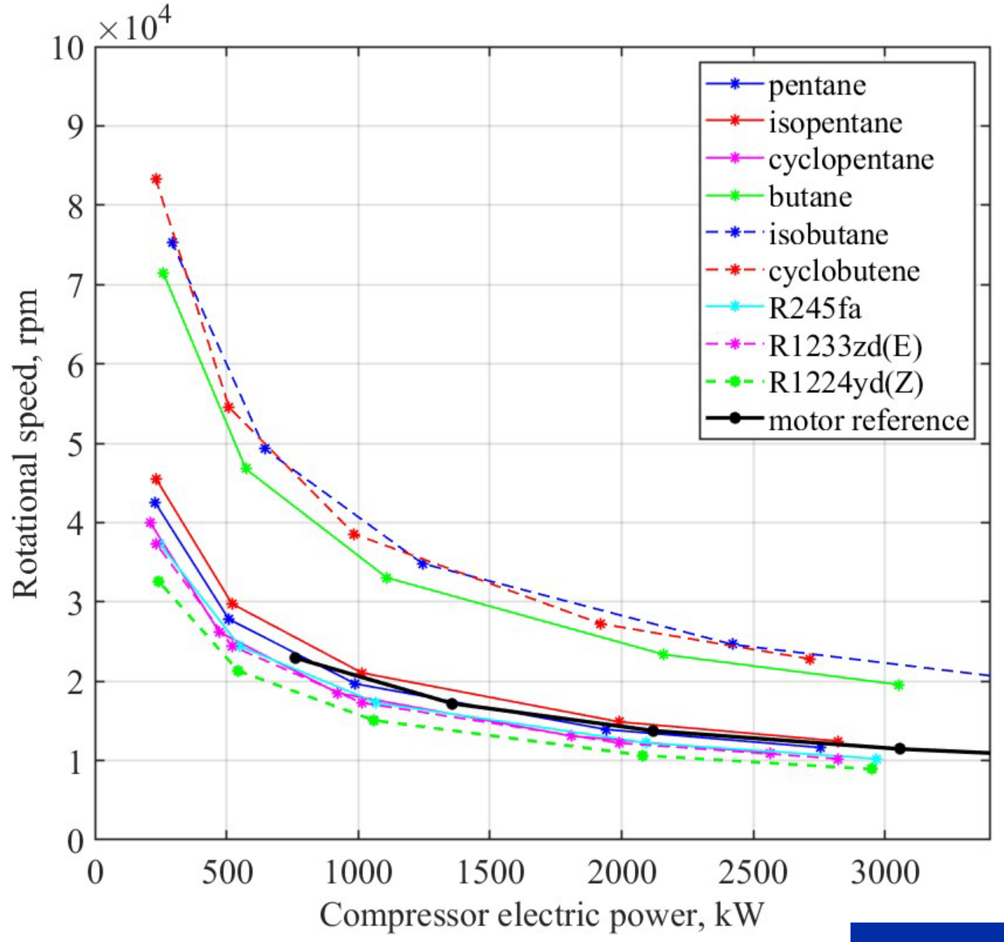
Task 1.1: Compressor

- Preliminary design of the centrifugal type of compressor for the heat pump was done to evaluate the working fluid on the compressor design.
- Investigation found that low molecular mass hydrocarbons result in high rotational speed compressors, for which existing standard electric motors are not available.



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Task 1.1: Working fluid selection

- Investigation of working fluids resulted in a selection table that can be used to evaluate the suitability of working fluids.
- Pentane was selected as the best option for further investigation and as a working fluid for the heat pump.

Table 6.1: Summary of potential fluids.

Fluid name	COP	Evaporator pressure @ 20 ^{o}C	Superheating	Flammability	Future legislation	Compressor design
pentane	high	below atmospheric pressure	required	highly flammable	can be used	feasible
isopentane	high	below atmospheric pressure	required	extremely flammable	can be used	feasible
cyclopentane	high	below atmospheric pressure	required	highly flammable	can be used	feasible
butane	moderate	above atmospheric pressure	can be required	extremely flammable	can be used	fast rotating
isobutane	low	above atmospheric pressure	can be required	extremely flammable	can be used	fast rotating
cyclobutene	high	above atmospheric pressure	not required	NA	can be used	fast rotating
propane	low	high	not required	extremely flammable	can be used	extremely fast rotating
CO_2	transcritical cycle	very high	not required	non-flammable	can be used	extremely fast rotating
Ammonia	moderate	high	not required	flammable	can be used	extremely fast rotating
R1233zd(E)	high	above atmospheric pressure	can be required	non-flammable	P-FAS (and F-gas regulation)	feasible
R1224yd(Z)	moderate	above atmospheric pressure	can be required	non-flammable	P-FAS (and F-gas regulation)	feasible
R245fa	moderate	above atmospheric pressure	can be required	non-flammable	F-gas regulation and P-FAS	feasible

Task 1.2: Description and objectives

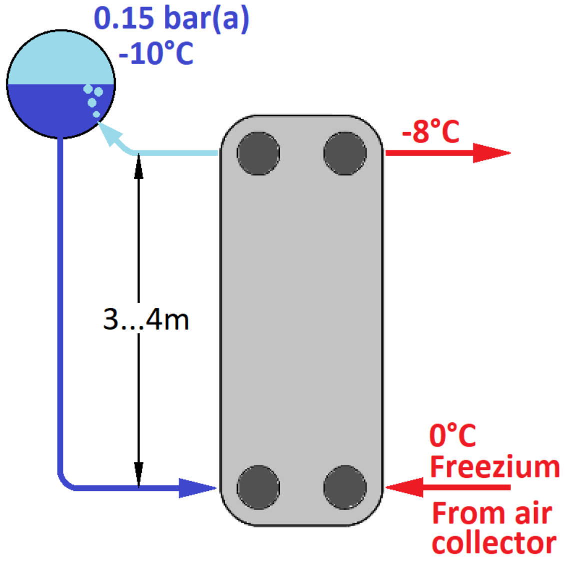
- The thermal design of the heat pump’s evaporator and condenser is conducted for a district heating application. The heat source of the heat pump is ambient air.
- The heat exchanger type selected was a plate heat exchanger.
- Numerical 1D models were built for the plate heat exchanger-based condenser and evaporator. A global stochastic optimiser was implemented to determine the optimal (lowest-cost) design.
- Heat exchanger design for pentane is compared with other selected working fluids. The working fluids are propane, butane and ammonia.

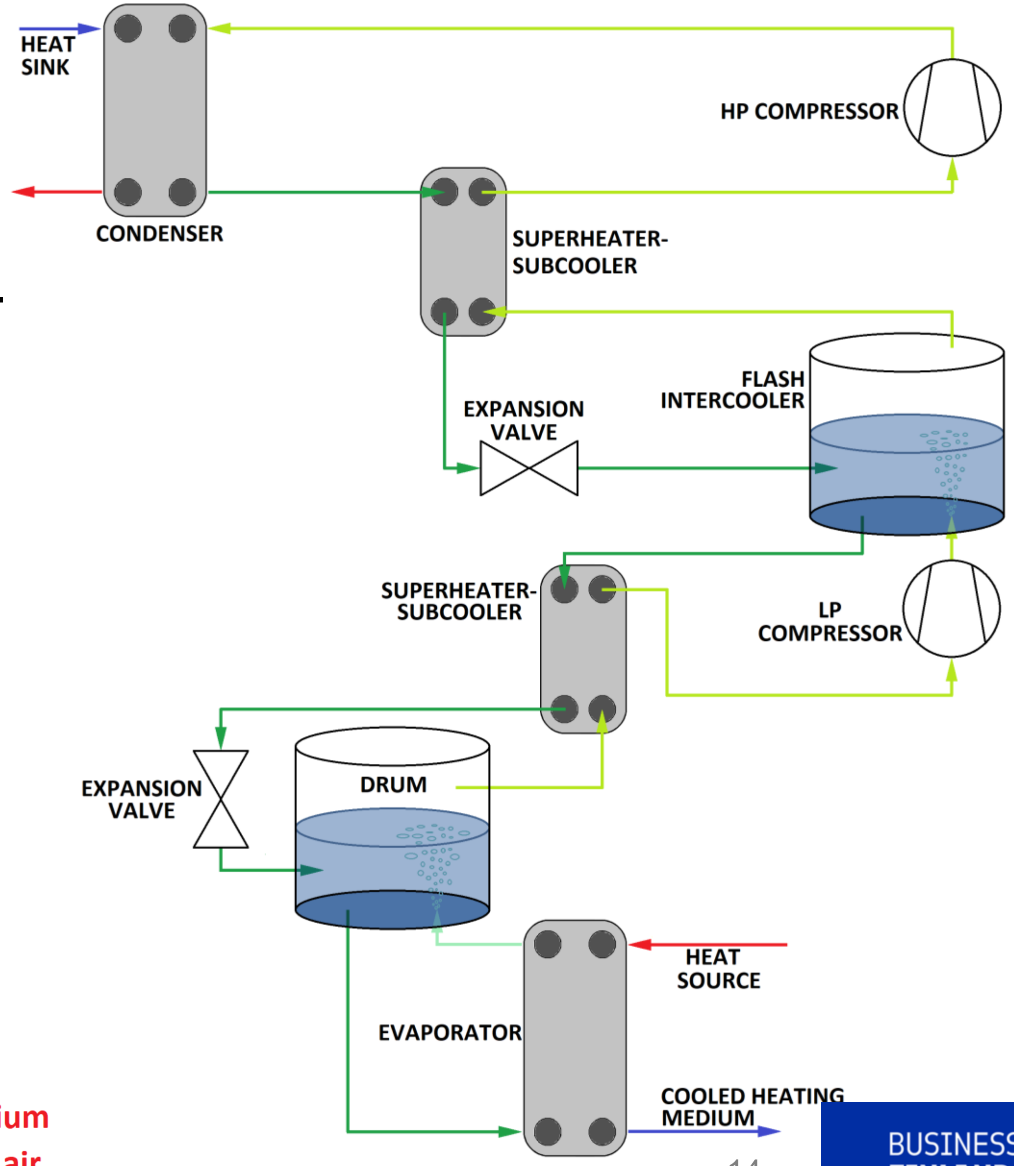
Objective

- Identify how working fluid selection influences heat exchanger design when the heat source of the heat pump is ambient air and heat is produced for district heating.

Task 1.2: Heat pump cycle

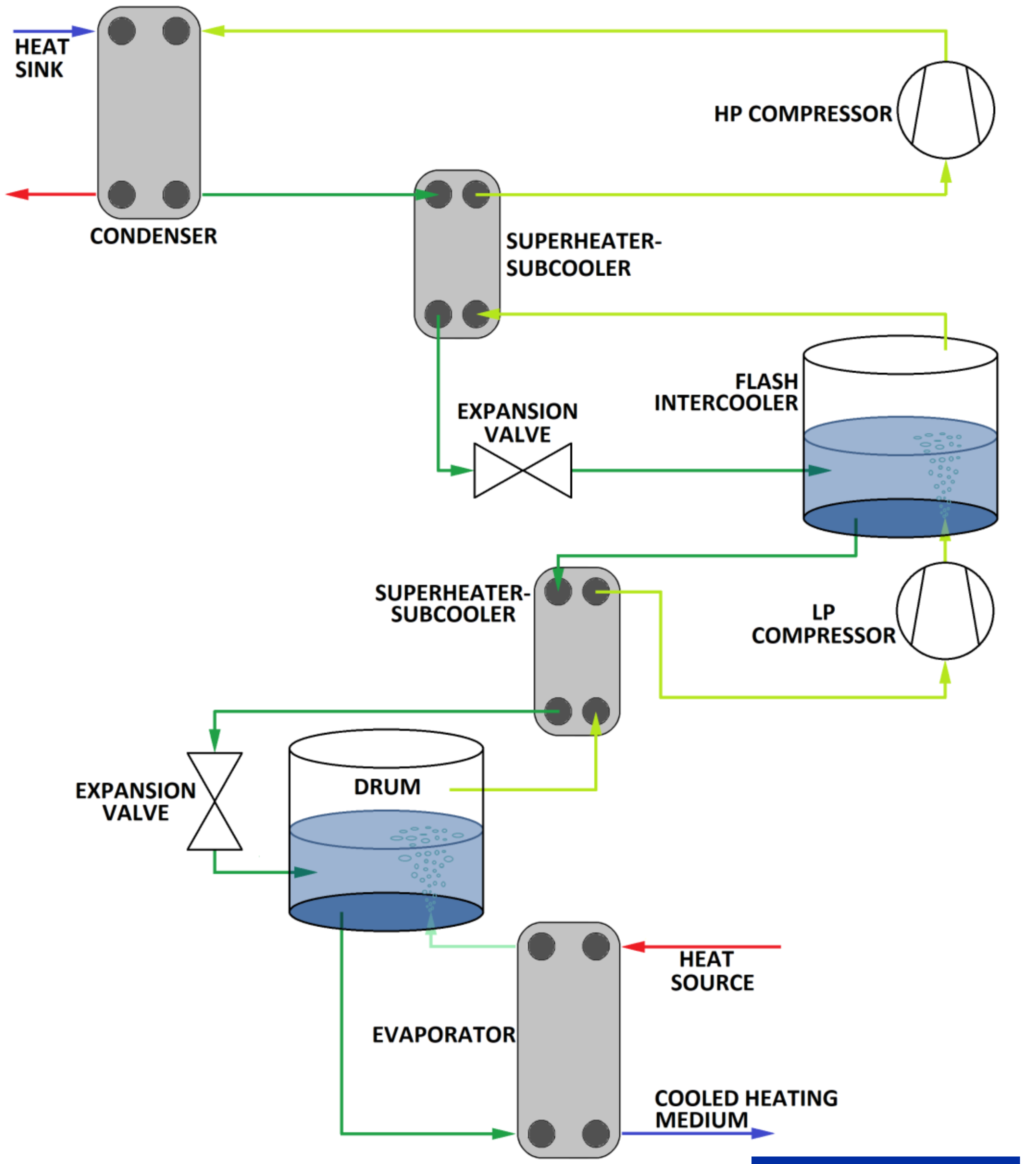
- The heat pump design cycle was designed when the heat exchanger design work was implemented.
- The selected heat pump process is two-stage with a flash intercooler and a natural circulation evaporator.
- The aim of the evaporator design aim is to prevent any droplets in the vapour stream from entering the compressor.
  - Solution: natural circulation loop with drum.
  - Any droplets escaping the drum will be few and small, and evaporate in the subcooler-superheaters.





Task 1.2: Evaporator

- Pentane is a challenging fluid for a heat pump using an ambient heat source.
  - Very large volumetric flow rate and low heat transfer coefficient.
  - → Large, expensive heat exchanger, for a 3.5 MW(th), installed cost in the order of at least 200 000 € .
- Butane improves heat transfer performance, and the cost of the evaporator is only 1/3 the cost of a pentane evaporator. However, butane may not be a feasible working fluid for a centrifugal compressor.
- Ammonia is superior to pentane by an order of magnitude in terms of equipment cost. However, ammonia is toxic and may not be a feasible working fluid for a centrifugal compressor.



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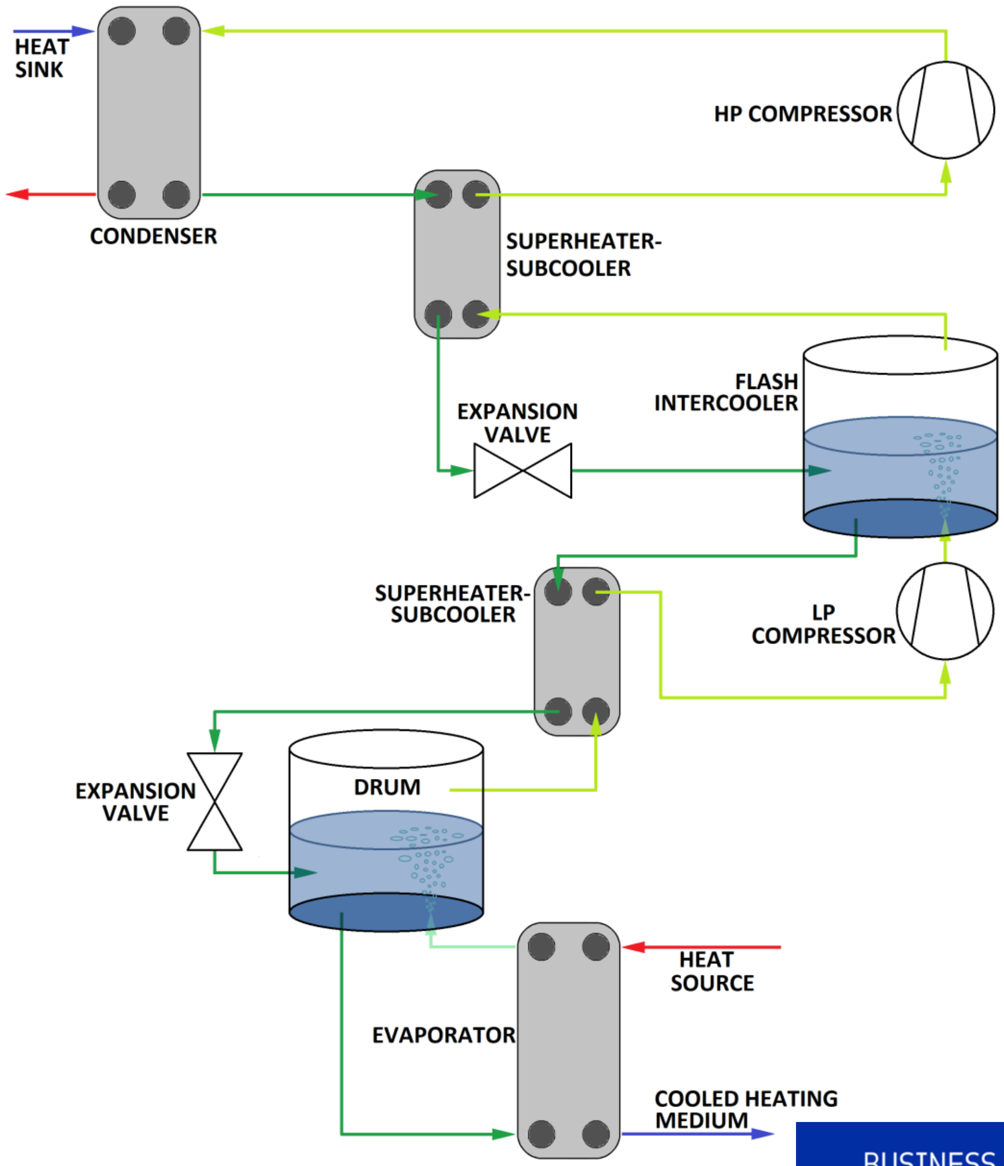
Task 1.2: Condenser

- Pentane condenser has challenges in obtaining good heat transfer compared to its peers. However, the margin is small. The condenser costs for alternative, conventional, and low-GWP fluids are within 30%.
- The heat exchanger design of the condenser is small and compact compared to the evaporator, with all investigated fluids.
- Compact design of the condenser results in low heat exchanger manufacturing costs, of which the working fluid selected arguably has an insignificant impact.



Task 1.3: Description and objectives

- The thermal design of the air-source heat collector field is created.
- A dynamic 1D semi-empirical fin-tube heat exchanger model is developed for thermal design of the heat collector unit. A computational fluid dynamics (CFD) model is developed for investigating gas flow within the air-source heat collector field.
- A heat collector is designed using the dynamic 1D model, and the frosting of the collector is evaluated.

Objectives

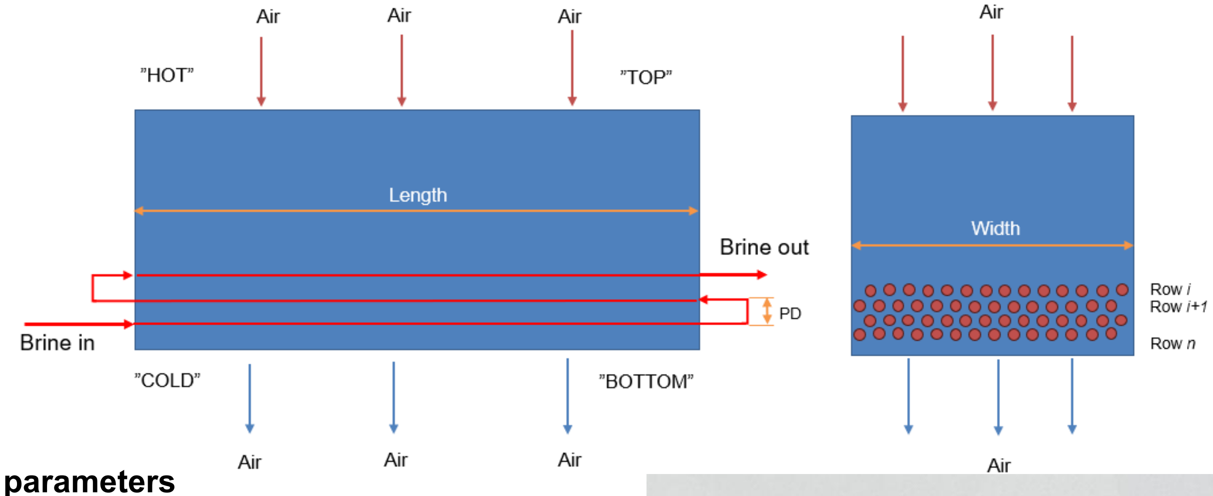
- Create a thermal design of the air-source heat collector field and identify how the layout of the field and ambient conditions affect its performance.
- Examine the influence of varying operating conditions on the performance of a single heat collector and its tendency to frost.
- Review the air-source heat collector field defrosting methodologies.

Task 1.3: Single fin-tube heat exchanger

Dimensions of heat exchanger

Parameter		
Length of unit	m	6.5
Width of unit	m	2.0
Height of unit	m	0.8
Elevation of unit (leg length)	m	4.0
Number of fans	pcs	8 (2x4)
Fan spacing		Even
Fan diameter	m	1
Tube internal diameter	mm	8.4
Tube external diameter	mm	10
Tube length	m	6.5
Number of parallel circuits	pcs	100
Number of tube passes	pcs	12
Passes distance (PD)	mm	20
Fin dimensions (square)	mm	20x20
Number of fins per tube	pcs	969
Fin thickness	mm	2
Fin spacing	mm	7
Tube configuration		Staggered
Tube material		Copper
Fin material		Aluminium

Heat exchanger configuration



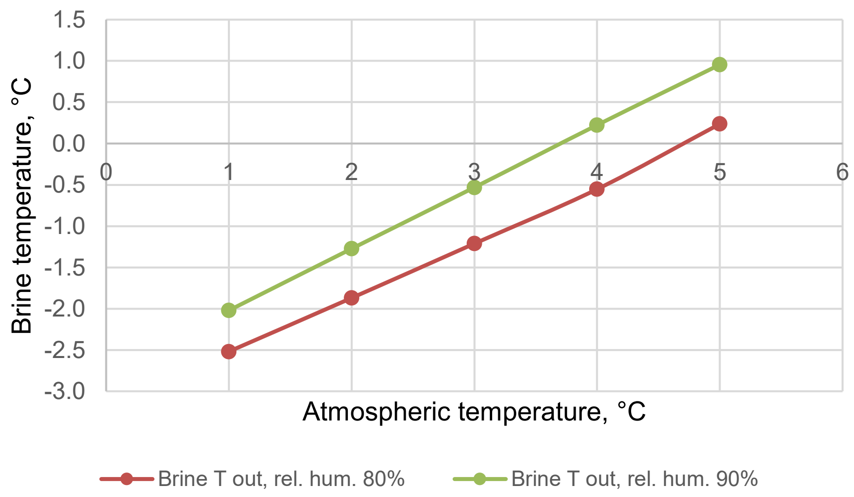
Operational parameters

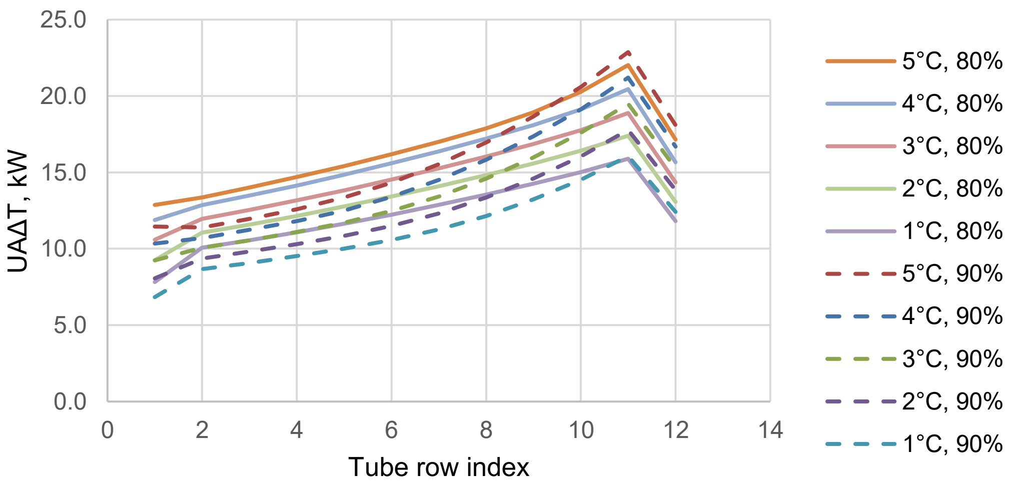
Parameter		
Brine total flow from the evaporator	kg/s	149
Airflow per fan	kg/s	7.5
Brine temperature	°C	-8
Air temperature	°C	5
Air relative humidity	%	80
Air pressure drop in heat exchanger	Pa	36
Brine pressure drop[1]	kPa	400
Ideal power consumption of field[2]	kW	76 kW
Power consumption / Thermal power	%	2.4

Illustration of heat exchanger

Task 1.3: Fin-tube heat exchanger performance

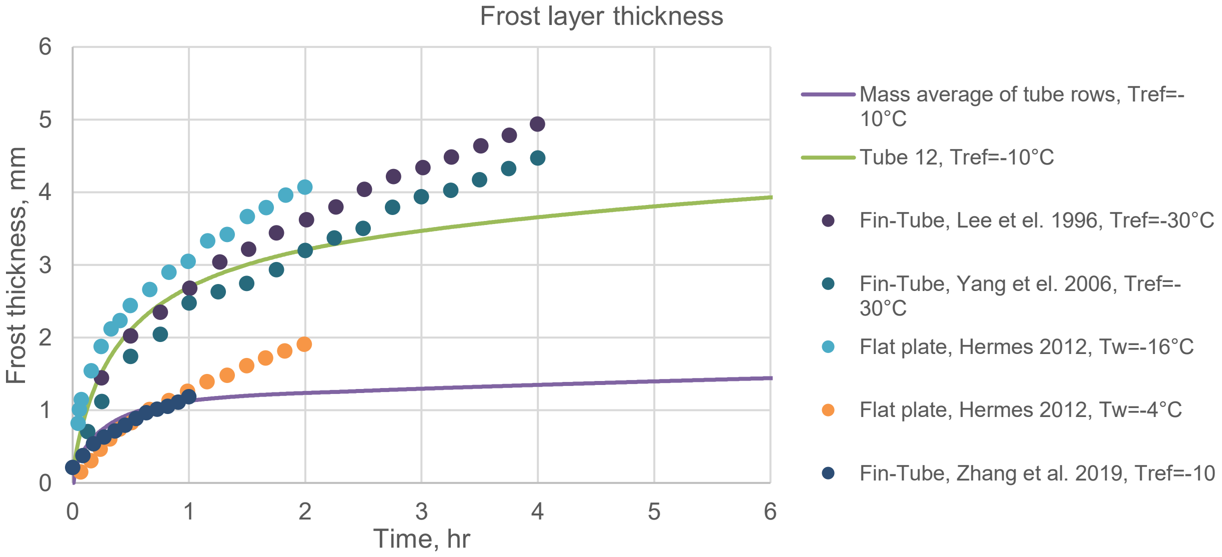
- The heat collector was designed using the 1D model. Performance of the field was investigated under varying atmospheric temperature and air humidity.
- The heat exchanger at the design point is not prone to frosting. The temperature of the heat exchanger internals is above the sub-zero temperatures. Frosting is likely to happen when the atmospheric temperature is close to zero.

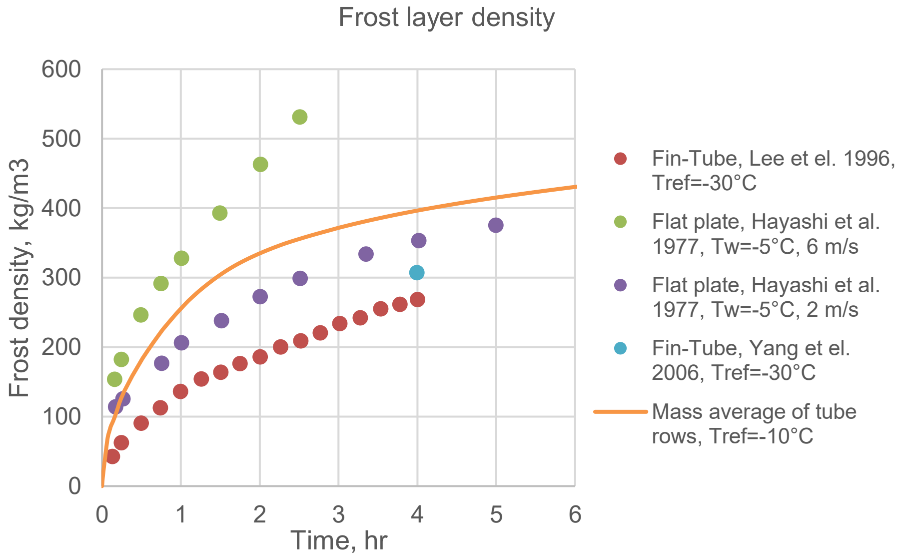




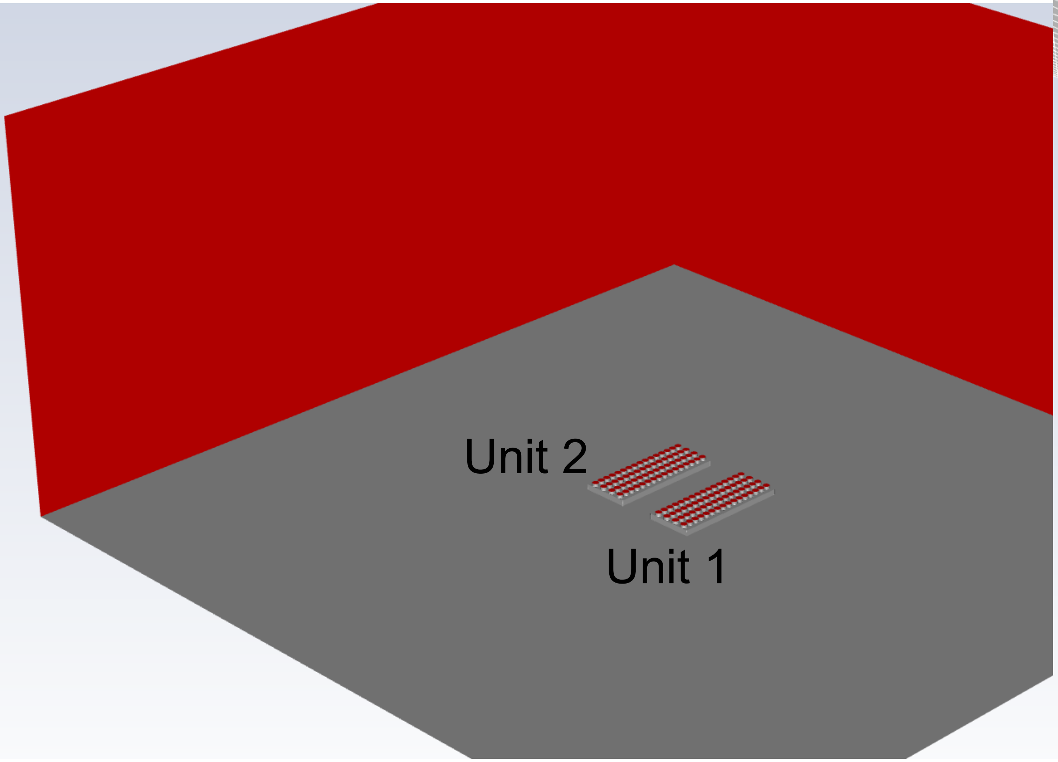
Task 1.3: Fin-tube heat exchanger frosting

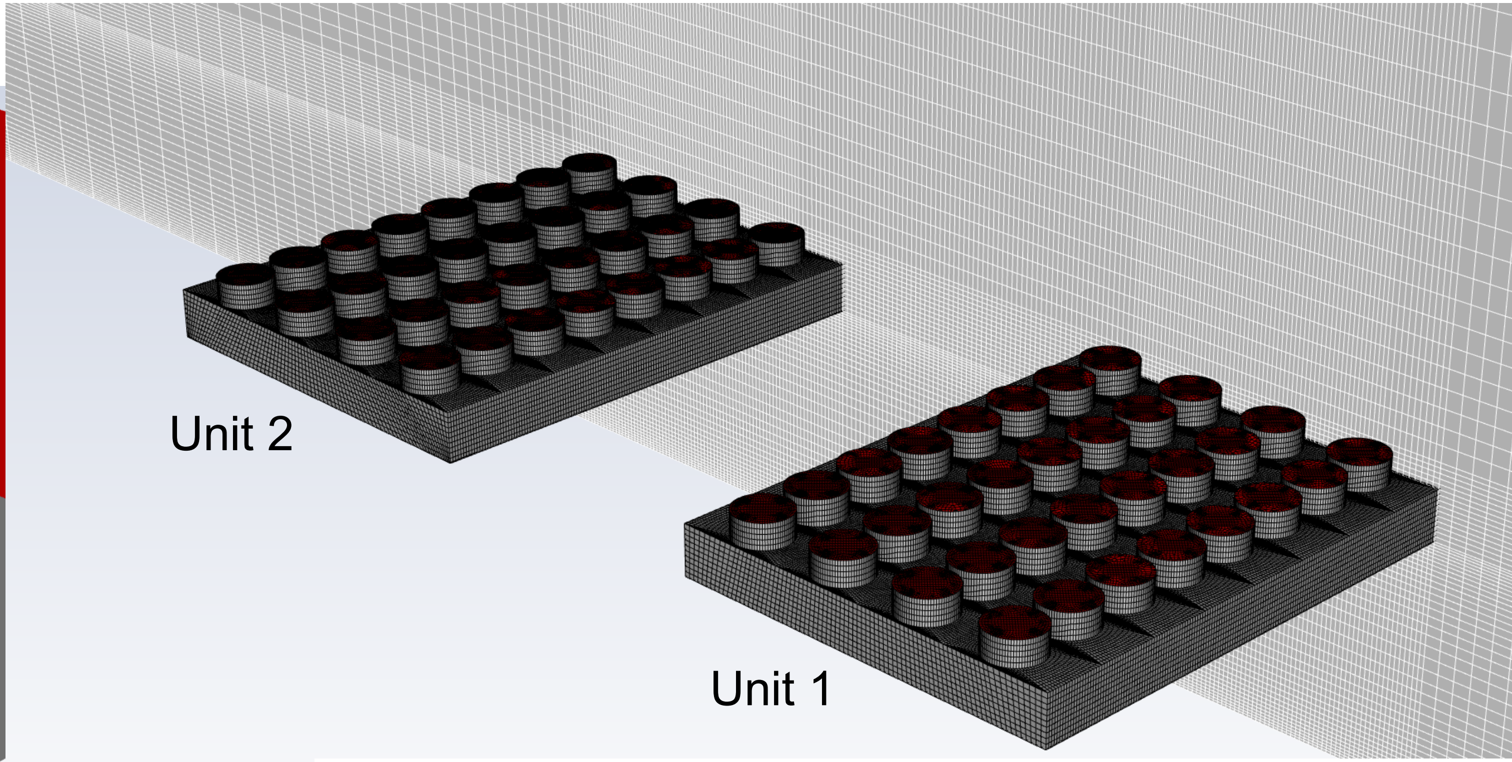
- The frosting of the heat exchanger was investigated under conditions where frosting is prone to occur. Lower atmospheric temperature and brine temperature were used than at the design point.
- The results can be used to evaluate the influence of frosting on the performance of the heat exchanger and the needed frequency of frosting cycle.





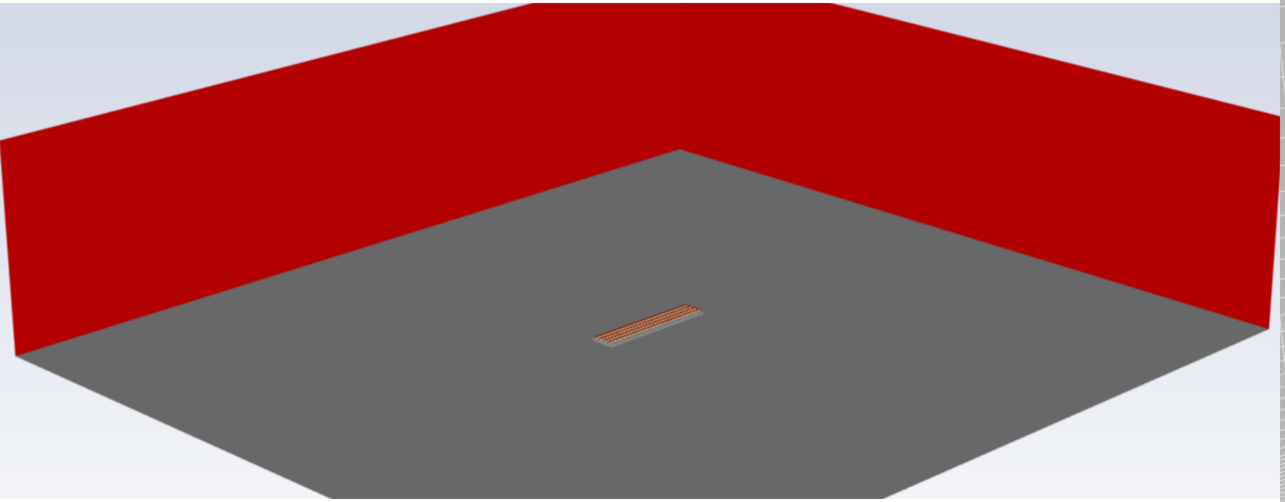
Task 1.3: CFD model, two collector groups

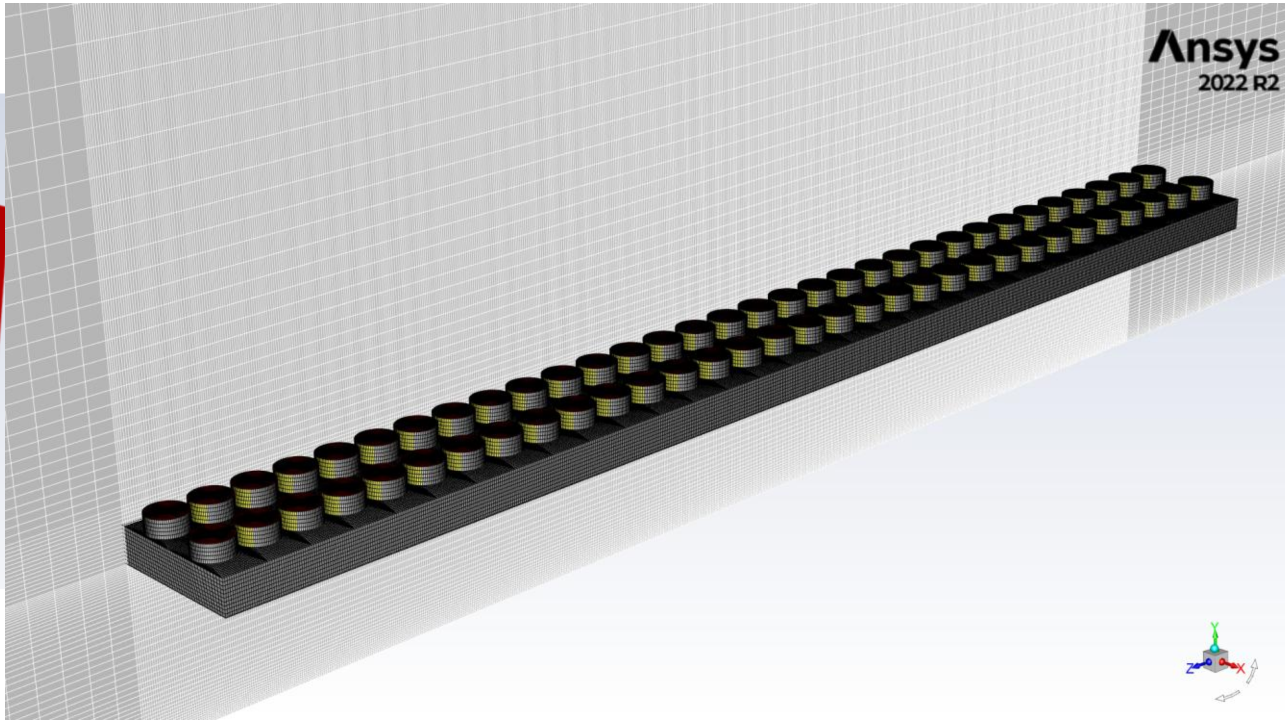




Plane cutting the geometry in half to illustrate the mesh

Task 1.3: CFD model, one collector group





Plane cutting the geometry in half to illustrate the mesh

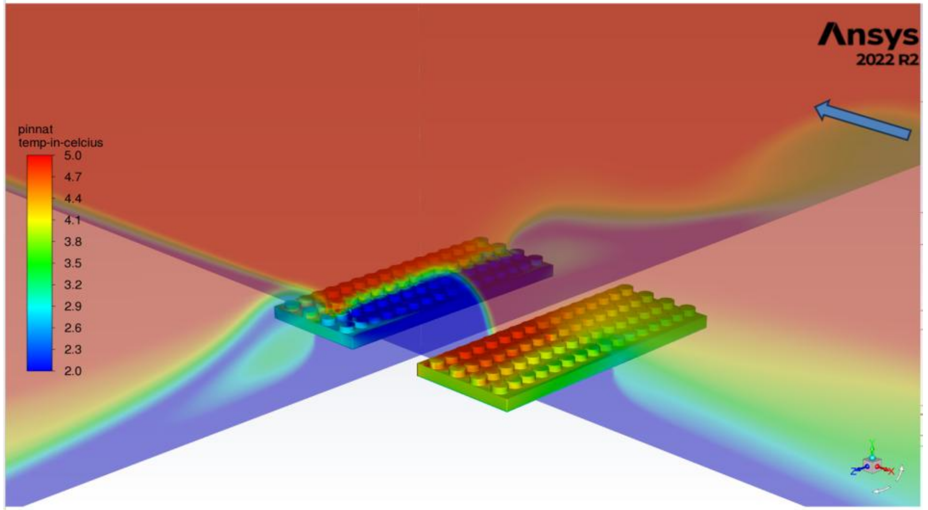
Task 1.3: CFD simulations

- CFD simulations and thermal design data were used to evaluate the thermal efficiency of the heat collector field with two major layer selections and different directions of wind and its speed.

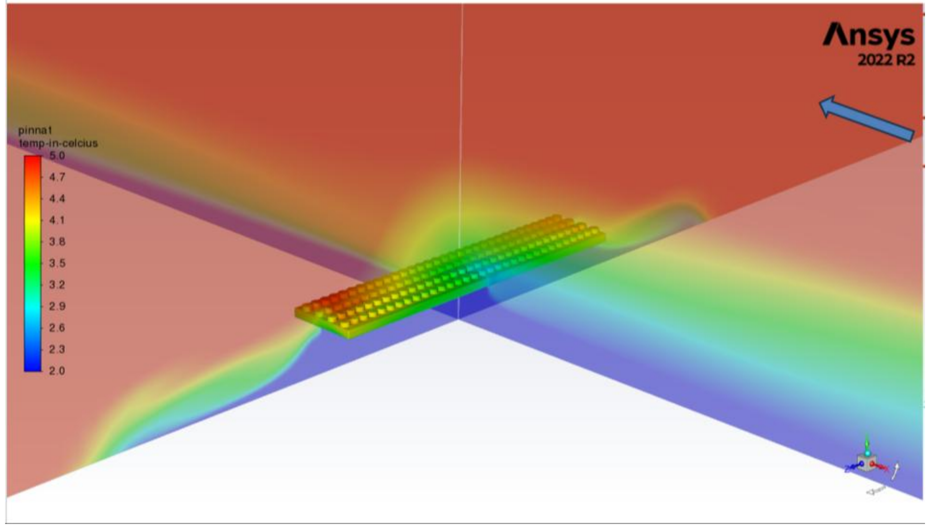
Table 4. Thermal efficiency of the units.

Case	Unit 1 efficiency	Unit 2 efficiency	Single unit efficiency
no wind, bt	98.3 %	84.9 %	98.4 %
2.5 m/s N, bt	92.4 %	86.6 %	
5 m/s N, bt	80.5 %	88.4 %	90.7 %
2.5 m/s E, bt	90.4 %	86.9 %	
5 m/s E, bt	90.6 %	90.3 %	98.3 %
no wind, dt	98.4 %	98.5 %	98.2 %
5 m/s N, dt	97.0 %	93.4 %	98.3 %
5 m/s E, dt	95.7 %	95.5 %	98.6 %

North wind 2.5 m/s



Single unit, North wind 5 m/s



WP 1: Conclusions

- Working fluids for high-temperature and high-speed heat pumps were identified. Future legislation could prevent the use of non-natural working fluids. Potential natural working fluids for the heat pump application were recognised. Pentane was selected as a potential candidate.
- The thermal design of the evaporator and condenser was investigated for district heat and air-source heat pump. Pentane, as the working fluid for the heat pump, was found to be challenging, especially for the evaporator design. Alternative working fluids investigated were found to be more suitable for the heat exchanger in selected conditions. However, their suitability for the centrifugal compressor is not good.
- Thermal design of air-source heat collector field created using 1D and CFD modelling. The influence of heat collector field layout and atmospheric conditions on thermal performance was identified.
- The influence of frosting on heat exchanger performance was investigated. The heat exchanger designed for the heat pump is not prone to frosting under design conditions. However, atmospheric temperatures close to zero and lower brine temperatures can induce frosting.

WP1: Main results

- Identification of suitable natural working fluids for high-temperature and high-speed heat pumps.
- Development of air-source heat pump cycle for high-temperature lift heat pump equipped with high-speed compressor technolgoy.
- Development of 1D steady-state semi-empirical codes for plate heat exchanger-based evaporator and condenser, and an optimisation algorithm for heat exchanger cost. Thermal design of evaporator and condenser for pentane, butane, propane and ammonia working fluids.
- Development of a 1D dynamic semi-empirical code for the air-source heat collector unit and a CFD model for the air-source heat collector field. Thermal design of the heat collector field. Evaluation of single collector frosting under varying operating conditions.

WP 1: Publications and Theses

Conference

- Jussi Saari, Antti Pitkäoja, Antti Uusitalo, Satu Lipiäinen, Jouni Ritvanen (2024). Economic optimization of a chevron-plate pentane evaporator for a modern high-temperature heat pump. Proceedings of ECOS 2024: The 37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. Url: https://www.proceedings.com/content/077/077185-0108open.pdf

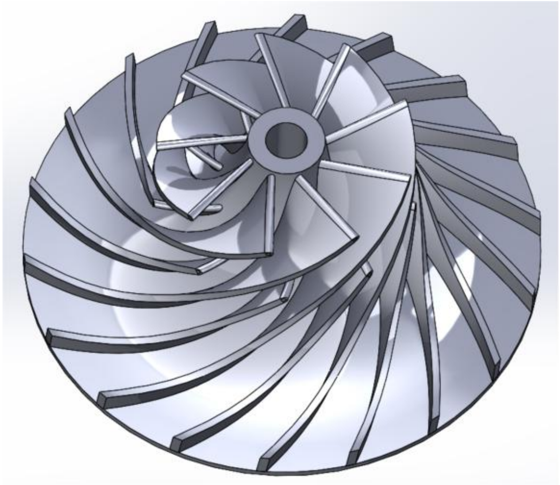
Master thesis

- Eemeli Koivu. Comparison of direct and indirect evaporators in an air-source heat pump. 2023. Url: https://lutpub.lut.fi/handle/10024/166518

WP 2: High-speed turbo compressor and electrical motor development to create a hermetic high-power component for future heat-pump systems

Task 2.1: Compressor aerodynamic design

- Aerodynamic design and loss analysis methods of high efficiency centrifugal compressors were investigated.
- Compressor designs and compressor aerodynamic design with different refrigerants was carried out.
- Main focus was on two-stage centrifugal compressors for high temperature heat pumps.
- The aerodynamic design was linked with motor, bearing and rotordynamic design of the hermetic compressor unit providing the necessary design input information for these components.
- The research was done in a close collaboration with WP1 and Tasks 2.2-2.4.

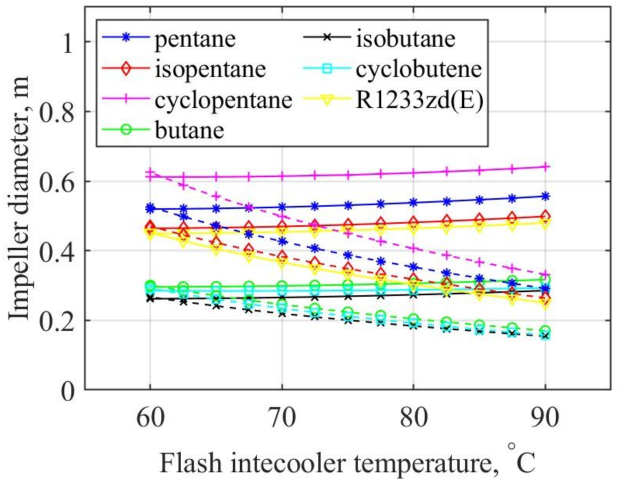


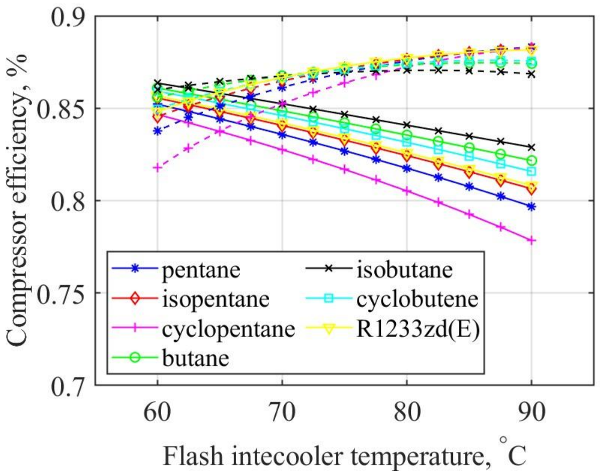
Task 2.1: Results

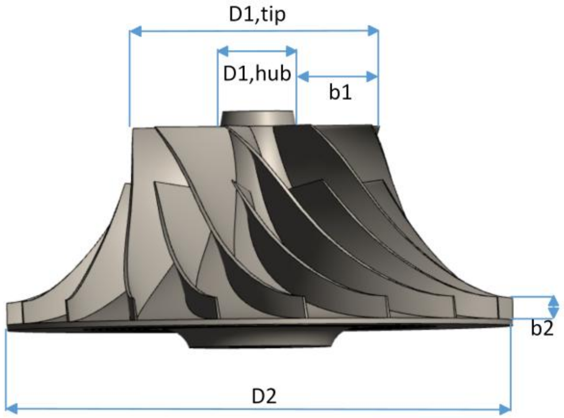
- Design and loss analysis method was developed for centrifugal compressor impeller design, which enabled to investigate the compressor aerodynamic design with different refrigerants and compressor design conditions.

- Real gas fluid properties were included by using thermodynamic and transport property databases for accurate estimations of the fluid properties (Coolprop and Refprop were utilized)

- The model estimates the main dimensions of the compressor impeller and diffuser as well as predicts the compressor efficiency by using enthalpy loss correlations for the different loss sources (disk friction, tip clearance, skin friction, blade loading, recirculation, mixing and diffuser loss)





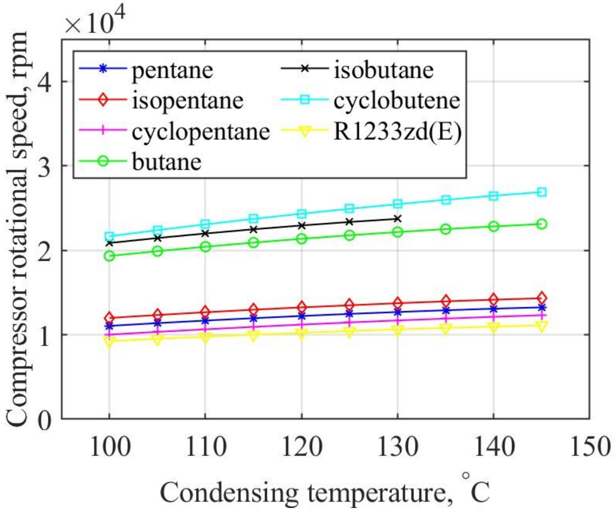


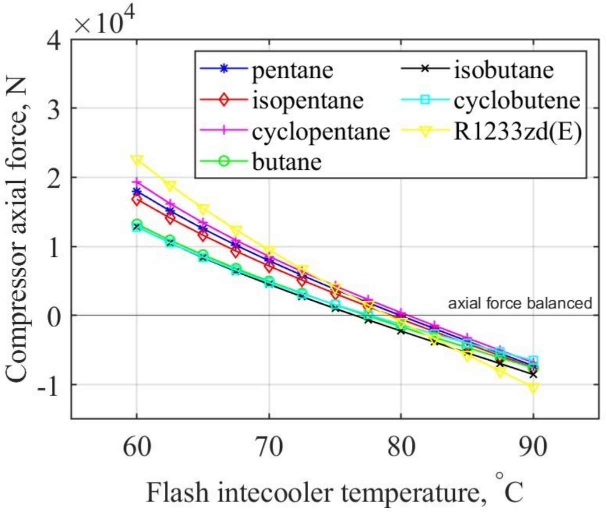
Task 2.1: Results

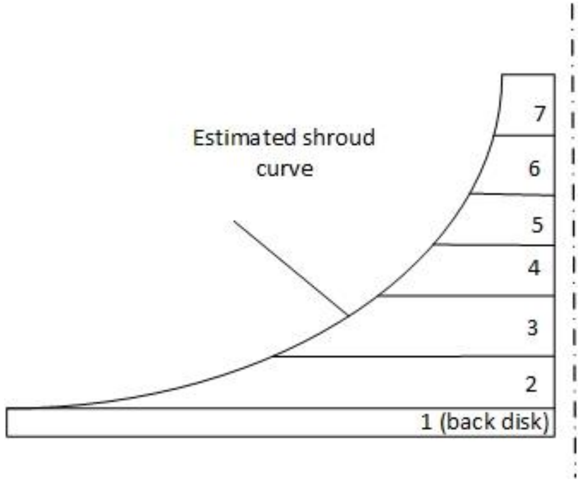
- The compressor aerodynamic design model can be used for estimating a suitable shaft rotational speed for the compressor unit with different refrigerants, compressor capacities, and design conditions.

- The developed compressor design and analysis model also includes estimations of axial forces acting on the impellers and impeller inertia.

- The compressor impeller designs, axial force and impeller inertia are utilized in the motor, bearing and rotodynamic analysis in Tasks 2.2-2.4.







Impeller model divided to elements to estimate polar and diametral inertia and center of gravity

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Task 2.1: Conclusions

- A robust, yet accurate aerodynamic design and analysis method for heat pump centrifugal compressor impellers was realized.
- Compressor aerodynamic design with different refrigerants including hydrocarbons, CO_2 and hydrofluoro-olefins were carried out and investigated.
- Generally, centrifugal compressors were observed being an efficient compressor type for large-scale high temperature heat pumps (isentropic efficiencies close or above 80 %) .
- Shaft rotational speeds, compressor dimensions and efficiency were highly affected by the design point parameters, refrigerant and capacity of the heat pump system.
- Especially with high temperature lifts, the flow becomes supersonic with hydrocarbons and with many synthetic refrigerants. To avoid supersonic flow conditions, a higher number of impeller stages must be used (3-4 stage compression).

Task 2.2: Motor design

- Description:
  - Development of high-speed electrical motor design methodology for centrifugal compressors based on the requirements of high-temperature heat pump processes.
- Objectives:
  - Develop methods for selecting the appropriate motor size and type for heat pump processes, along with tools to match motor specifications to system data, including motor-impeller integration for turbomachinery developers and performance calculations.
  - Conduct a comprehensive study on the full integration of the electric motor into the heat pump system, including the compatibility of motor insulation and impregnation materials with heat pump process fluids.

Task 2.2 Results

- The most suitable type of electric motor for heat pump applications is a solid rotor, copper-cage induction motor.
  - Robust structure suitable for hermetic construction.
  - Tolerant of high temperatures.
- In hermetic construction, ATEX regulations need not be considered because there are no leaks.
- The hermetic structure places special demands on the electrical insulation, as the insulation is in direct contact with the natural refrigerant.
  - Swelling and softening of insulating materials.
  - Conventional polyesterimide impregnation resin must be replaced with epoxy.
  - In hermetic construction, all non-metallic materials in the insulation structure must be tested with the refrigerant used; no standard certifications exist.
    - Exposure testing with explosive gas needs dedicated laboratory.

Task 2.2: Results

- A computer program was developed in the project to design a solid-rotor, copper-cage induction machine based on impeller power and rotational speed inputs. Depending on the rotor material, its dimensions are constrained by the maximum allowable surface speed and by tangential stress, which accounts for thermal and electromagnetic limits.
  - The code designs a suitable short-pitched three-phase winding arrangement for the lowest possible voltage level. Once the machine dimensions, winding, and electrical parameters are calculated, the code evaluates the machine’s electromagnetic performance.
  - Calculation results (dimensions and losses) are used in the thermal and rotordynamic analyses.

Task 2.2: Conclusions

- For low-voltage machines (U < 1000 V), shaft power could theoretically reach 3-4 MW, depending on the cooling solution. However, as the shaft speed and, therefore, the supply frequency increase, there will be a need to switch to higher voltage levels. This increases the total cost of the electric drive but, at the same time, provides more flexibility in the electrical machine design.
- The developed computer code has been integrated into the overall design platform, connecting electrical machine design with impeller design, AMB design, and rotordynamic analysis.

Task 2.3: Rotor dynamics of AMB-supported integrated heat pump compressor

- The compressor shaft, including the impellers and the active part of the electric machine, must be equipped with bearings.
- Active magnetic bearings (AMBs) were selected as the bearing solution to provide a lubrication- and maintenance-free option.
- From a design perspective, the challenge with AMBs is that they must be designed on a case-by-case basis, depending on the electric machine and the impellers.
- A second challenge arises from rotor dynamics and vibration control. In a first place, all rotating parts must have design that analyses can be executed. A second, initial design might be non-feasible, requiring the design changes in previous design steps.
- Therefore, the objectives for Task 2.3 are:
  - To develop a design code to generate an instant geometrical design for AMBs.
  - To develop an analysis code for rapid simulations of rotor dynamics and AMB control.

Task 2.3: Results

- In a project was developed the design process and code for automation computing of AMB geometry. Flowchart describes the design process and the design areas in AMB design.
- Calculation includes:
  - Two axial AMB geometries.
  - One radial AMB geometry.
  - Low and high frequency force capacities (dynamics force capability).
  - Mechanical stresses after assembly and in top speed.
  - Temperatures on AMB windings and required cooling.
- Two publications from the AMB design process are submitted for review.

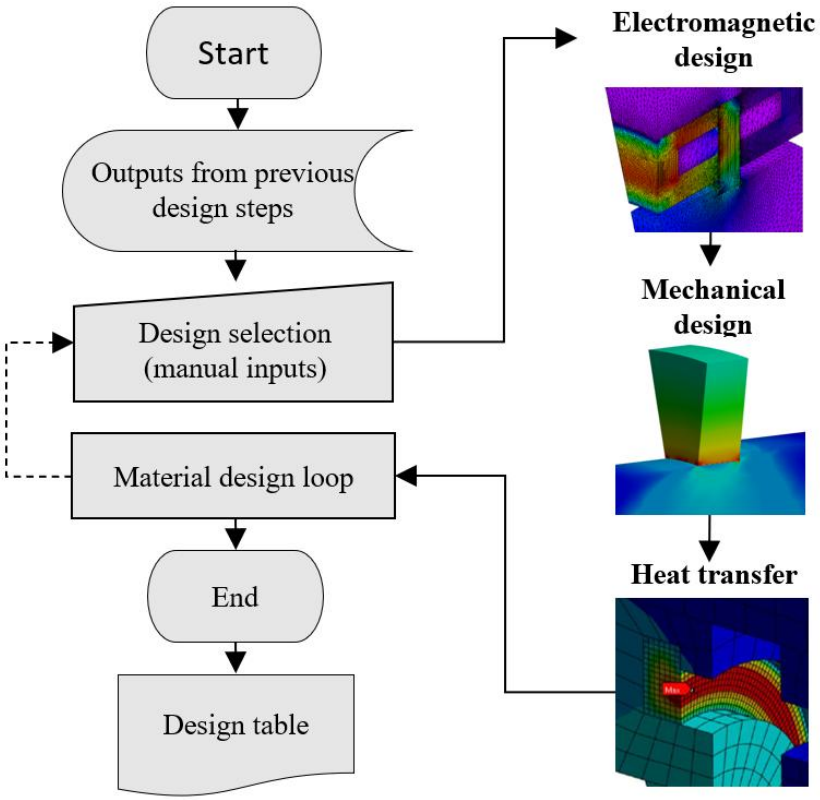

Fig. Simplified flowchart of AMB design basing on selections and steps leading to design tables.

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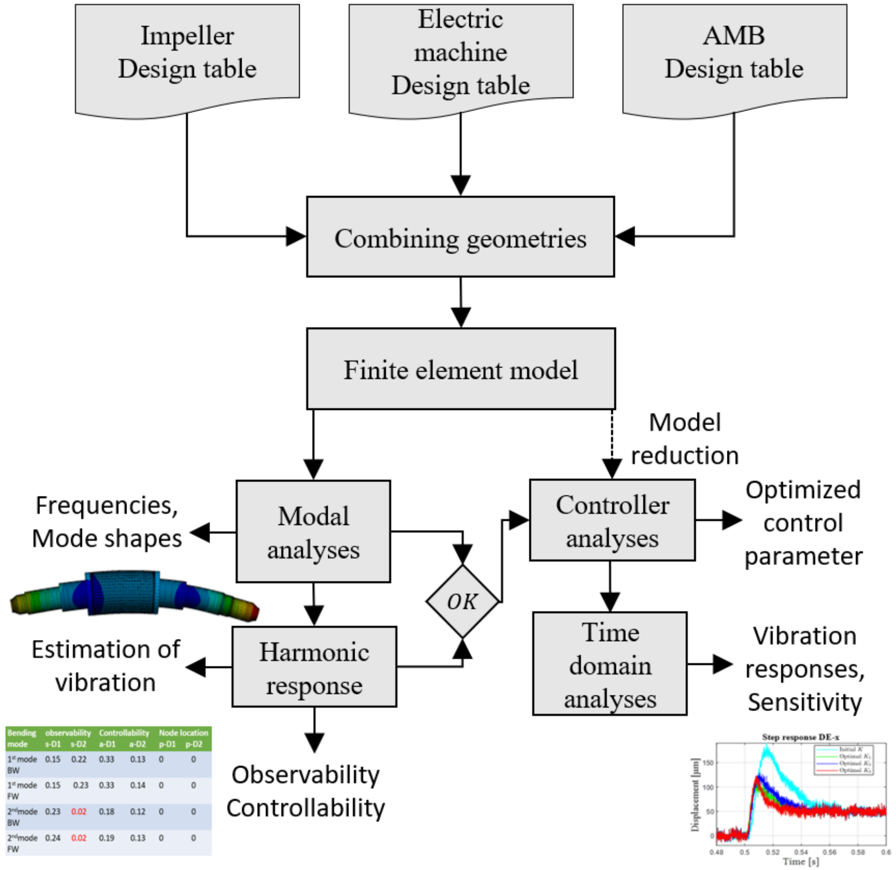
Task 2.3: Results

- For rotor dynamic analyses, the RoBeDyn code- developed over the past two decades under Prof. Jussi Sopanen was utilized. Code will automatically build a mathematical expression of given geometry (results of impeller, electric machine and AMB designs) resulting e.g., natural frequencies, critical speeds and unbalance responses. The same mathematical model are utilized in the AMB control design
- Based on the baseline rotor-AMB design:
  - A control feasibility check is performed by examining the observability and controllability of the machine. This helps determine the necessary next steps in the control design or indicates whether a step back in the design process is required
  - A reduced-order rotor-AMB model for control design is obtained, which is required for synthesis, analysis, and simulation.

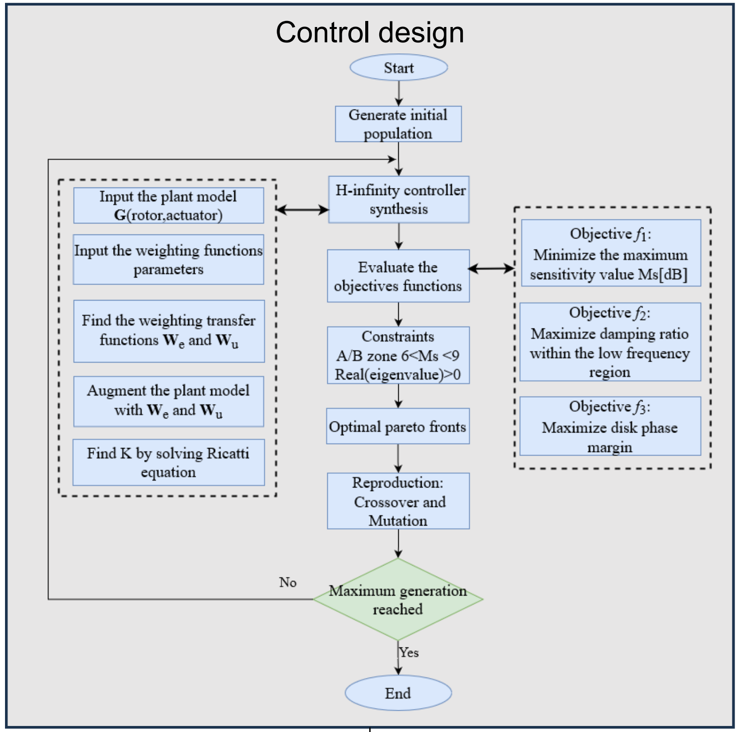


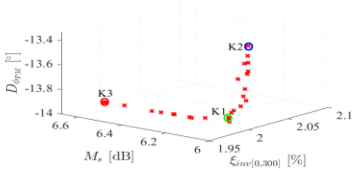
Bending mode	observability s-D1	s-D2	Controllability a-D1	a-D2	Node location p-D1	p-D2
1st mode BW	0.15	0.22	0.33	0.13	0	0
1st mode FW	0.15	0.23	0.33	0.14	0	0
2nd mode BW	0.23	0.02	0.18	0.12	0	0
2nd mode FW	0.24	0.02	0.19	0.13	0	0

Fig. Simplified flowchart of the design process, from design tables and geometry integration to FEM model generation for analysis.

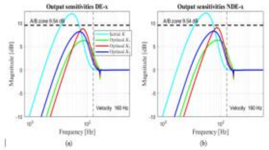
Task 2.3: Results

- The control design is based on a model-based controller, where the rotor-AMB model is used for synthesis. The design is formulated as a multi-objective optimization problem, guided by criteria such as stability, mode damping, and output sensitivity.
- Suitable candidates are evaluated using the Pareto front to assess trade-offs, with engineering intuition providing guidance in selecting the controller based on performance and robustness.
- Two articles of the AMB control design process and parameter optimization have been published





Optimized control parameters / Controller candidates



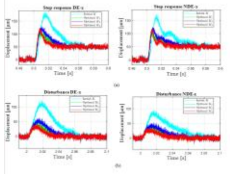


Fig. Model-based control design with an optimization routine. The obtained controller is evaluation/analyzed in time/frequency domain.

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Task 2.3: Conclusions

- **Rotor-AMB design:** A semi-automated design for the AMB rotor system reduces the engineering work by providing a baseline design
- **Control design:** Tuning the AMB control system requires expertise, and the design is often based on manual selection and tuning. Optimization relaxes this problem and provides the possibility to systematically search for the optimal parameters

Task 2.4: Coupled design

- In the task 2.4 a coupled design of the heat pump system and compressor unit was developed and investigated.

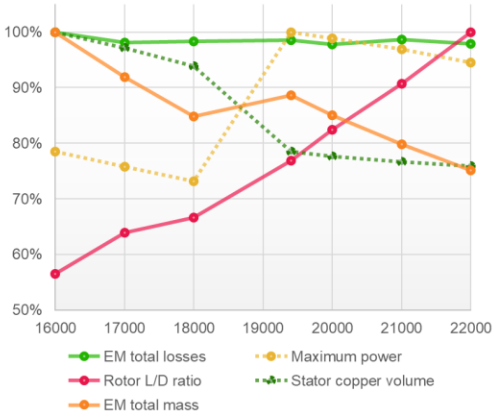
- The main task was to generate a co-design method of the compressor unit, including the impeller aerodynamic design, motor design and cooling with the refrigerant, bearing design and control as well as the rotor dynamic analysis connected to a same design and analysis tool.

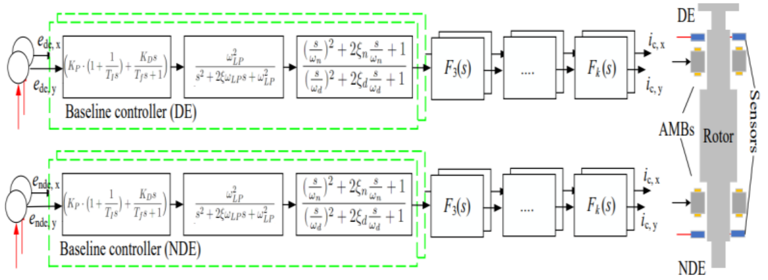
- The compressor design inputs, including the inlet temperature and pressure, fluid mass flow rate and outlet pressure were gained from heat pump cycle calculations and the results of the compressor unit loss estimation was used to improve the accuracy of the COP prediction in the cycle model.

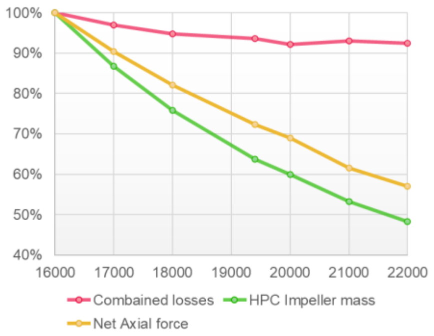
Task 2.4: Results

- A detailed centrifugal compressor co-design and loss analysis method was developed.
- Allows to estimate the feasibility of compressor design and it’s performance with different refrigerants and heat pump design operating conditions
- Compressor design for LUT 1 MW heat pump facility under construction was selected as the main design case

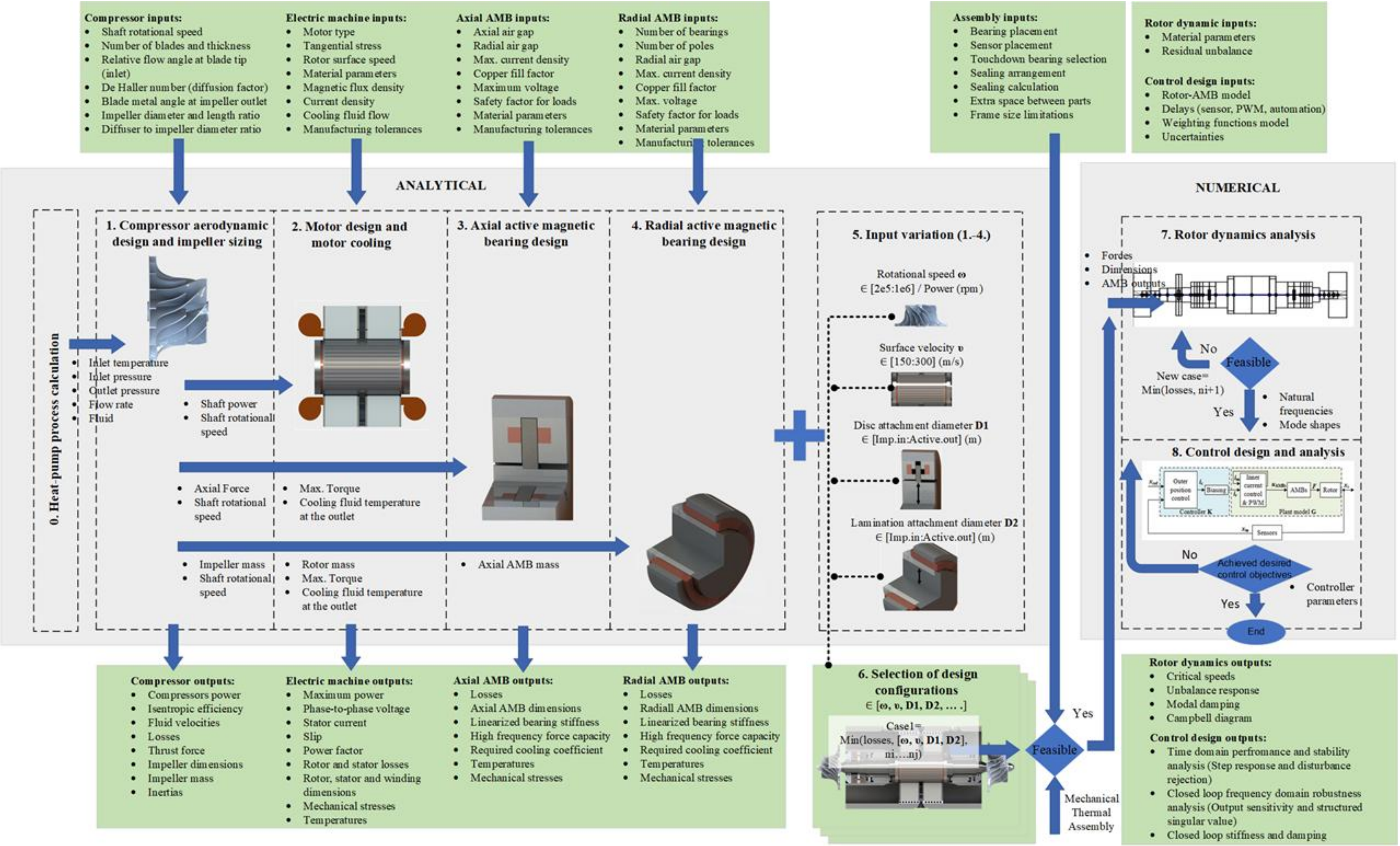
Parameter	16000	17000	18000	19400	20000	21000	22000	Unit
EM total losses	21,18	20,77	20,82	20,88	20,71	20,9	20,73	kW
Electrical Efficiency	95,7	95,8	95,8	95,7	95,7	95,8	95,8	%
Maximum power	795	767	741	1012	1001	981	956	kW
Active part length	131	139	137	148	152	161	169	mm
Rotor diameter	215	202	191	177	172	164	156	mm
Rotor L/D ratio	0,61	0,69	0,72	0,83	0,89	0,98	1,08	
Stator outer diameter	536	497	478	494	476	449	425	mm
Stator L/D ratio	0,24	0,28	0,29	0,3	0,32	0,36	0,4	
Rotor copper volume	1139	1118	1064	870	866	869	870	mm^3
Stator copper volume	5591	5431	5246	4391	4338	4288	4241	mm^3
Rotor mass	54,9	53,5	51,5	42,5	42	41,7	41,4	kg
Stator mass	193,6	172,5	155,5	182	172,3	157,8	145,1	kg
Winding mass	42,5	41,3	39,9	33,4	33	32,6	32,2	kg
EM total mass	291	267,3	246,9	257,8	247,3	232,1	218,7	kg





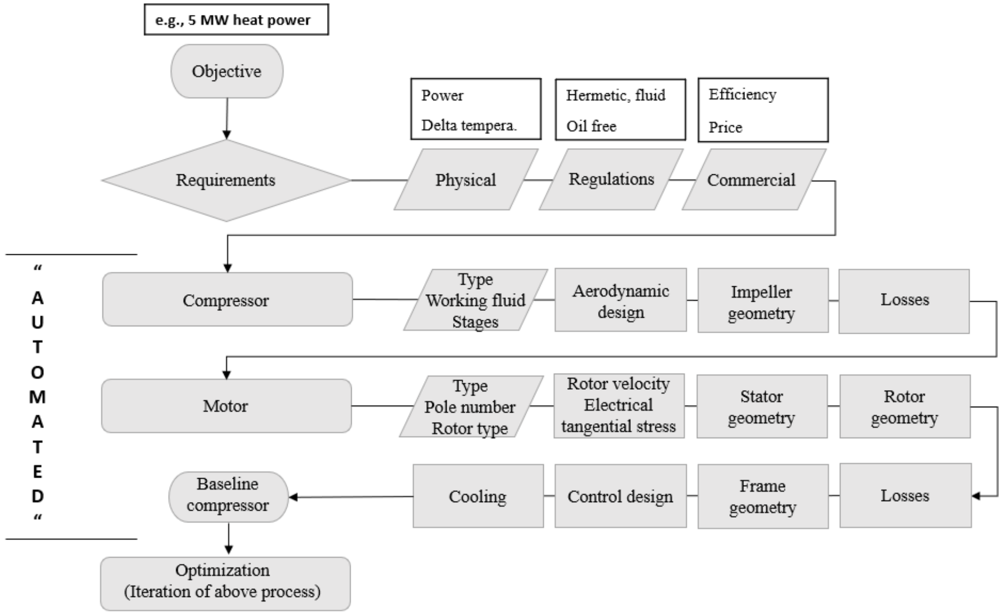


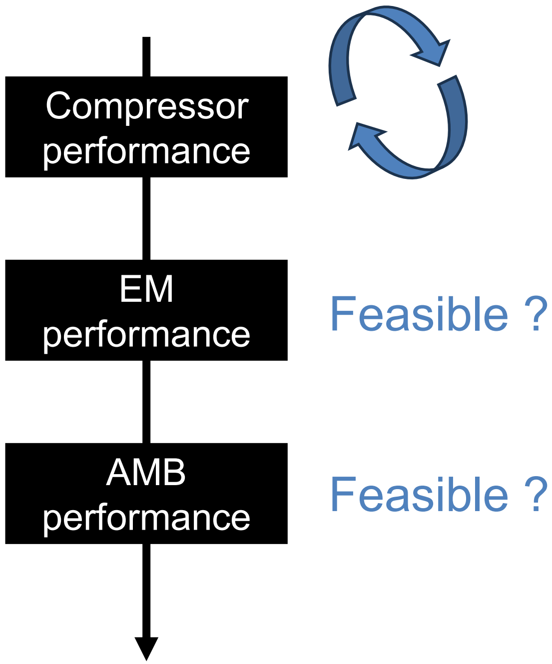
Task 2.4: Results



Task 2.4: Conclusions

- A novel co-design method and calculation tool was developed for the compressor unit.
- In the future the tool can be used for optimizing compressor design with different optimization goals and for evaluation the most feasible compressor design from large design spaces.
- A journal publication is under preparation describing the developed method.





WP 2: Publications

- Journal publications:

“Centrifugal compressor design for high-temperature heat pumps”. Jaatinen-Värri, A., Honkatukia, J., Uusitalo, A., & Turunen-Saaresti, T. 2024, Applied Thermal Engineering. https://www.sciencedirect.com/science/article/pii/S1359431123021166

“Centrifugal compressor design and cycle analysis of large-scale high temperature heat pumps using hydrocarbons”. Uusitalo, A., Jaatinen-Värri, A., Turunen-Saaresti, T., Honkatukia J., Tiainen J. 2024 Applied Thermal Engineering. https://www.sciencedirect.com/science/article/pii/S1359431124007038

“Centrifugal compressor design analysis for large-scale transcritical carbon dioxide heat pumps” Uusitalo, A., Jaatinen-Värri, A., Turunen-Saaresti. 2024 Applied Thermal Engineering. https://www.sciencedirect.com/science/article/pii/S1359431124020234

“Optimizing PID Controller Design for Rotor Systems Suspended by Active Magnetic Bearings” Ibrahim Abubakar, Atte Putkonen, Marek Rehtla, Tuomo Lindh, Stijn Derammelaere and Niko Nevaranta 2024 Modeling, Identification and Control. https://lutpub.lut.fi/handle/10024/168897

WP 2: Publications

- Conference proceedings:

“DESIGN CONSIDERATIONS FOR A HIGH-TEMPERATURE HEAT PUMP CENTRIFUGAL COMPRESSOR” Jaatinen-Värri, A., Tiainen, J., Honkatukia, J., Uusitalo, A., Turunen-Saaresti, T. 2023 European Conference on Turbomachinery Fluid Dynamics and Thermodynamics (ETC)

“High-speed electric machine frame design process using topology optimization” Topi Kainulainen, Juuso Narsakka, Jussi Sopanen 2024 ICEM international conference of electric machines

“High-speed induction-machine squirrel-cage rotor mechanical design evaluation” Juuso Narsakka, Tuhin Choudhury, Juha Pyrhönen, Janne Nerg, Jussi Sopanen. 2024 ICEM international conference of electric machines

“Optimization of H∞-Control for Active Magnetic Bearing Suspended Rotor System” Ibrahim Abubakar, Muhammad Numan, Atte Putkonen, Tuomo Lindh and Niko Nevaranta. 2025 IEMDC 2025: International Electric Machines and Drives Conference

“Flow and loss analysis of centrifugal compressors for Trans-critical CO_2 heat pump applications” Arooj A., Uusitalo A., Turunen-Saaresti T., 2025 38th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems – ECOS 2025

WP 2: Theses

- “Design of centrifugal compressors for large scale transcritical CO2 heat pumps.” Mäki-Iso, Mikko 2023 https://lutpub.lut.fi/handle/10024/166142

- “DESIGN PROCESS FOR STRUCTURAL DYNAMICS OPTIMIZATION OF HIGHSPEED ELECTRIC MACHINE FRAME” Topi Kainulainen 2023 https://urn.fi/URN:NBN:fi-fe20231124148778

WP 3: Heat pump process integration and optimisation, energy system modelling

WP 3 : Heat pump process integration and optimisation, energy system modelling

- Efficient utilization of heat pumps requires good knowledge of the energy system that it is integrated with. The work package is divided into two tasks, 3.1 dealing with techno-economic analyses of a single heat pump units and 3.2 concentrating on integration of heat pumps to energy systems of communities

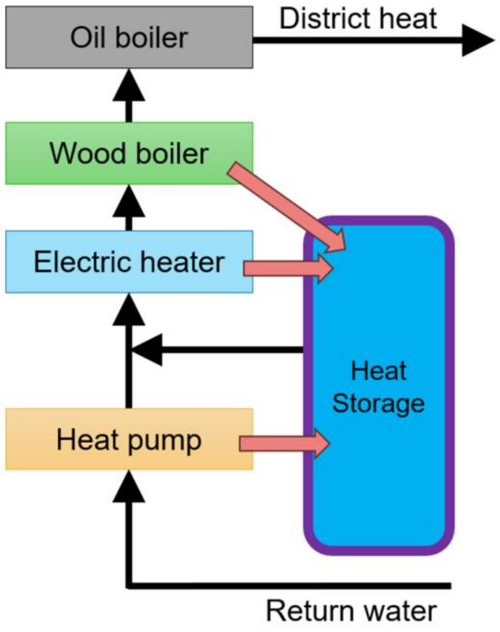
- The aim of the work package is to study and illustrate the potential of heat pumps in different energy systems for the end-users and technology providers from a perspective of single units and a larger system

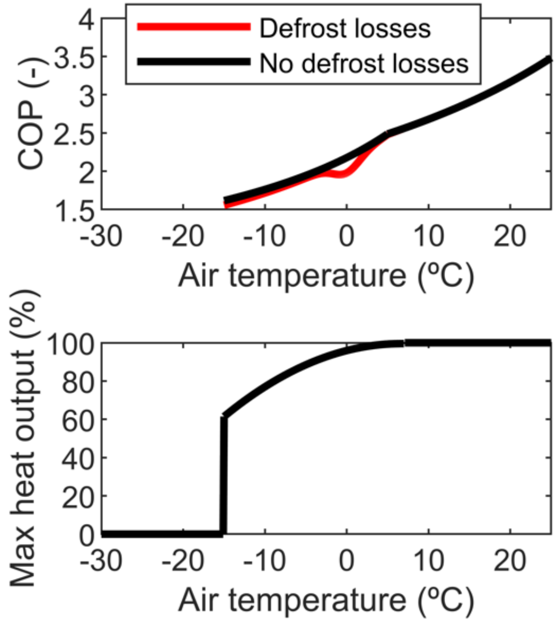
Task 3.1: Description and objectives

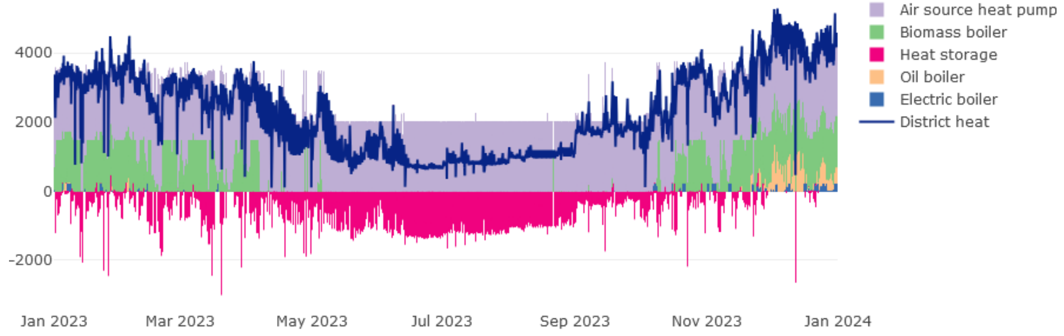
- The aim of the task is to find and present potential of heat pumps to reduce cost, emissions and energy consumption of heating (and cooling) at a specific application, by optimization of operation and unit capacities
- The objective at plant level is to develop a general parametrized, dynamic model that can be used with low effort for techno-economic case studies for various operating environments.
- It should be possible to include realistic unit models to consider aspects as temperature levels, off-design, and part-load operation.

Task 3.1: Results

- Two models were developed with objective to minimize cost of heat
  - Simplified but powerful mixed integer-linear programming (MILP) model in open-source Calliope framework → easy method for case studies and sensitivity analysis
  - A rule-based method in Matlab to optimize operation of a hybrid heating plant, connected to heuristic optimization of unit capacities → possibility to implement realistic non-linear unit models such as heat pump and thermal energy storage







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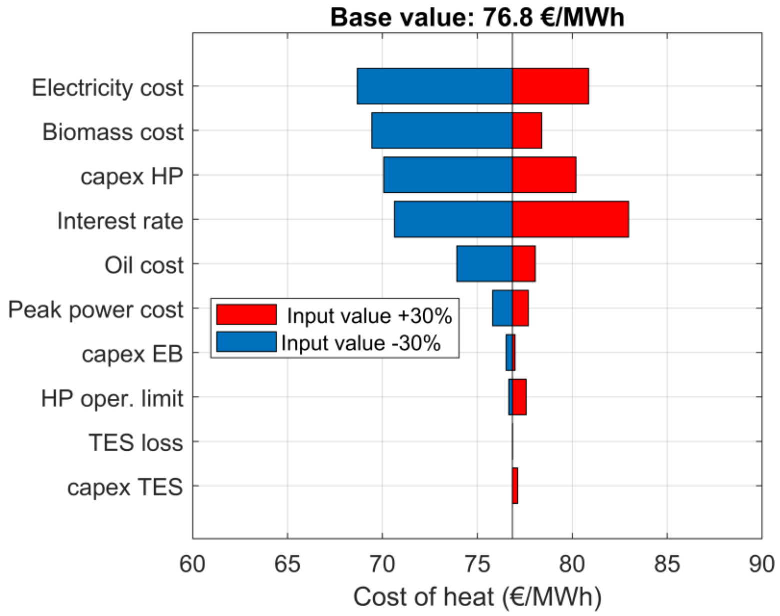
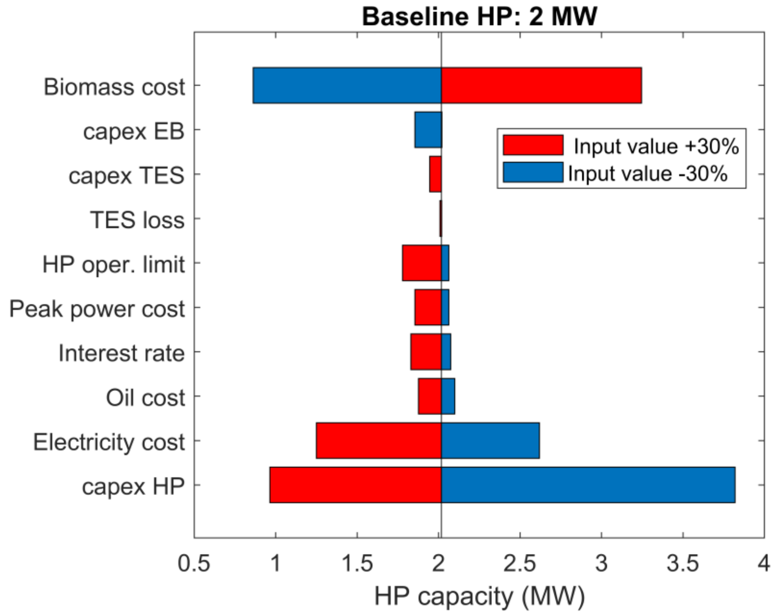
Task 3.1: Results

- Air-source heat pumps (HP) are often feasible, but there is high variation in the optimal capacity and operation with electric and biomass boilers → sensitivity analysis is important
- Also retrofitting HP to existing biomass-based district heat network can be feasible → typically providing baseload
- Electric boilers and heat pumps are partly competing/supplementing each other in electrification of heating
- Heat storage is valuable both with HP and electric boilers

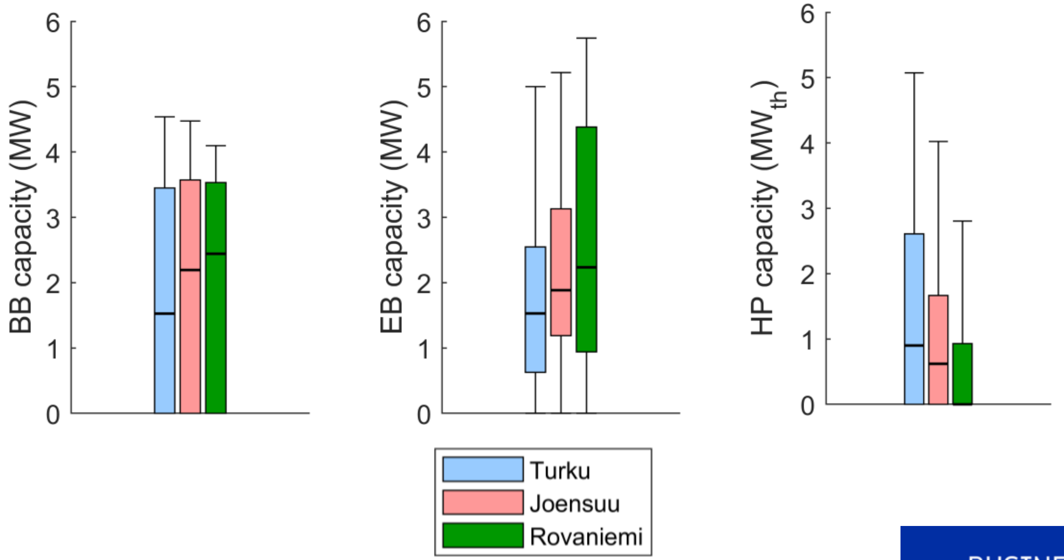




Task 3.1 Results

- Effect of climate on optimal capacity of air source heat pump, comparison between Turku, Joensuu and Rovaniemi
- In colder climate:
  - Decreased coefficient of performance (COP) and increased occasions of ambient temperature outside of the operation range of HP
  - Optimal HP capacity decreases → sometimes not feasible
  - Electric boiler (EB) capacity increases, compensating smaller HP
  - Biomass boiler (BB) capacity increases

Studied parameters (costs)	Low	Medium	High
Biomass cost (€/MWh)	20	35	50
Heat pump CAPEX (€/kW$_{th}$)	500	1000	1500
Electric boiler CAPEX (€/kW)	100	200	300



Task 3.1: Conclusions

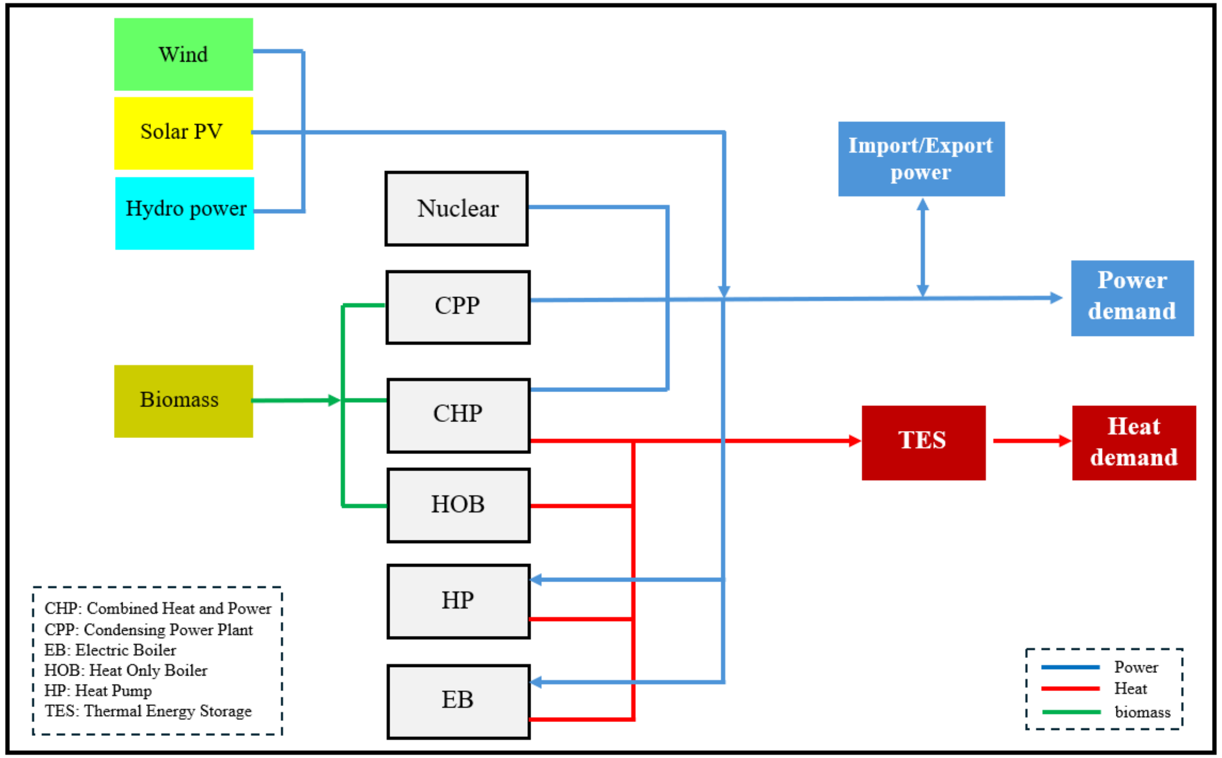
- Developed MILP model is powerful for case studies with sensitivity analysis
- More accurate rule-based model could be used to analyze different heat pump designs and refrigerants in realistic operation conditions
- Air-source heat pumps are often feasible, even as retrofit with existing biomass boilers
  - However, for example high investment cost of heat pump, low-cost biomass, cold climate, or high electricity cost can make heat pump infeasible → sensitivity analysis is essential
- Depending on costs and conditions, electric boiler can be supplementing or competing with heat pump
- Thermal energy storage seems feasible both for heat pump and electric boiler

Task 3.2: Description and objectives

- The aim of the task was to study the role of large-scale heat pumps in the future energy system in larger scale.
- The study includes two perspective, a city energy system and national Finnish energy system scale.
- The goal was to explore the benefits of integrating large-scale heat pumps into district heating networks, focusing on decarbonization, system integration, emphasizing the integration of temporally variable renewable energy, and cost savings from a socio-technological perspective.
- Key performance indicators, including critical excess electricity production (CEEP), total costs, and CO_2 emissions, are investigated.

Task 3.2: Results

- In the study, EnergyPLAN models were developed for the city of Savonlinna and the Finnish energy systems, including electricity and district heating sectors.
- In both case studies, EnergyPLAN reference case model was created based on current data (Savonlinna energy system in 2022 and Finnish energy system in 2023) and validated against statistics.
- In the city scale model, technical simulation strategy was utilized to minimize the CO2 emissions in the system.
- In national scale model market economic simulation strategy was utilized to minimize the socio-technological costs of the energy system.



Overview of the simplified Finnish energy system

Task 3.2: Results

- In both case studies, city and national level, several future scenarios were built with varying amounts of wind power and heat pump capacity.

- Only biomass, nuclear fuel and waste fuels used for the power plants
- Other components of the energy system are assumed to remain unchanged
  - No increase in electricity demand outside heating sector was considered

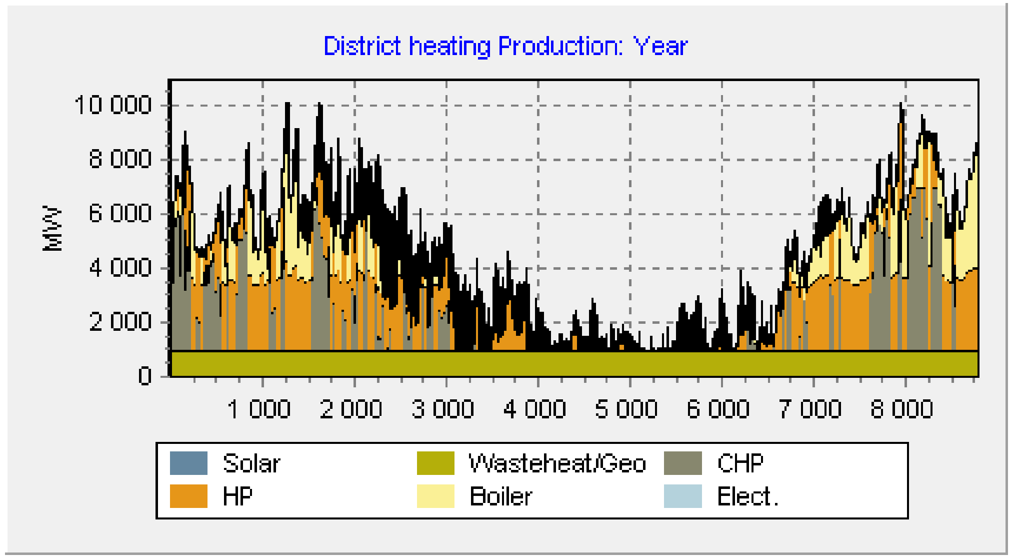


Figure 1. Moderate share of heat pumps in Finnish energy system.

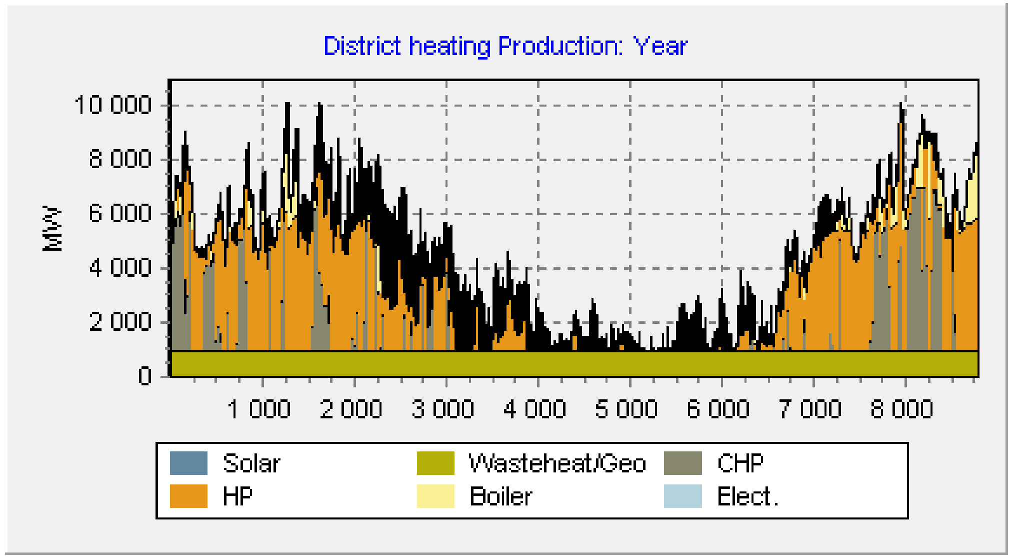


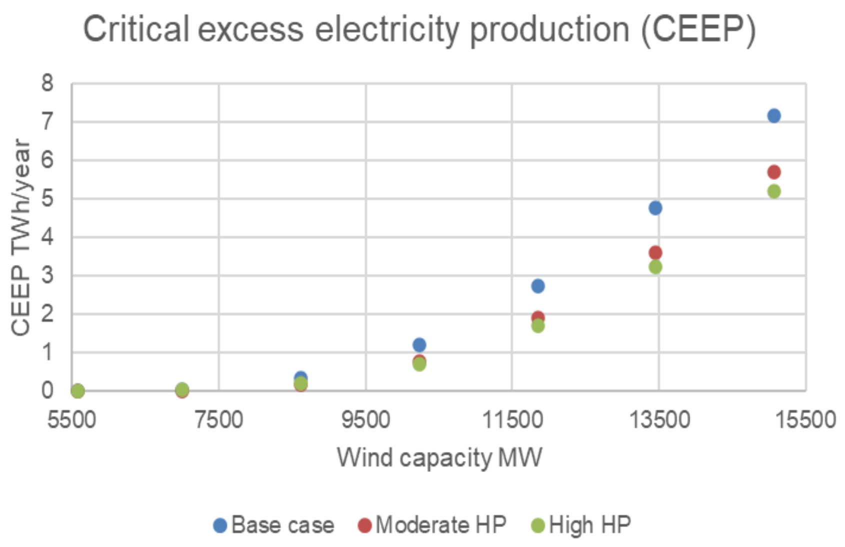
Figure 1. High share of heat pumps in Finnish energy system.

Task 3.2: Results

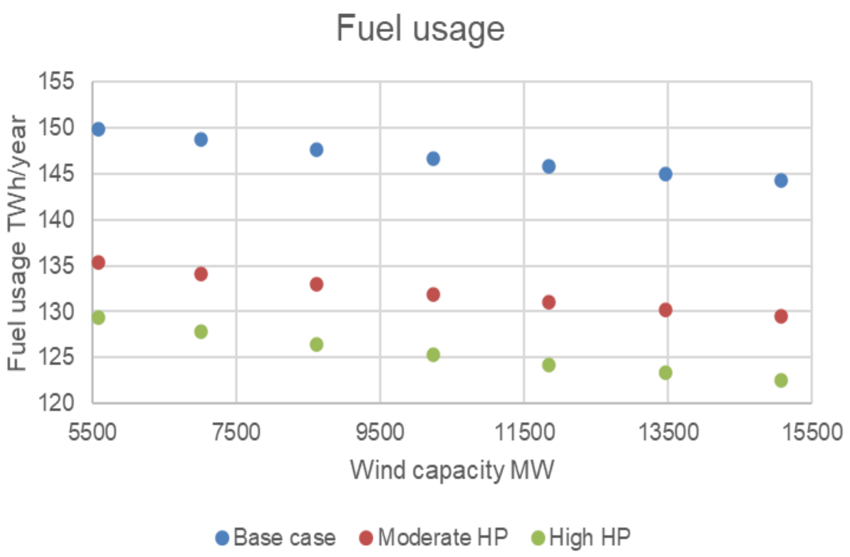
- The increasing capacity of heat pumps decreases Critical Excess Electricity Production (CEEP)

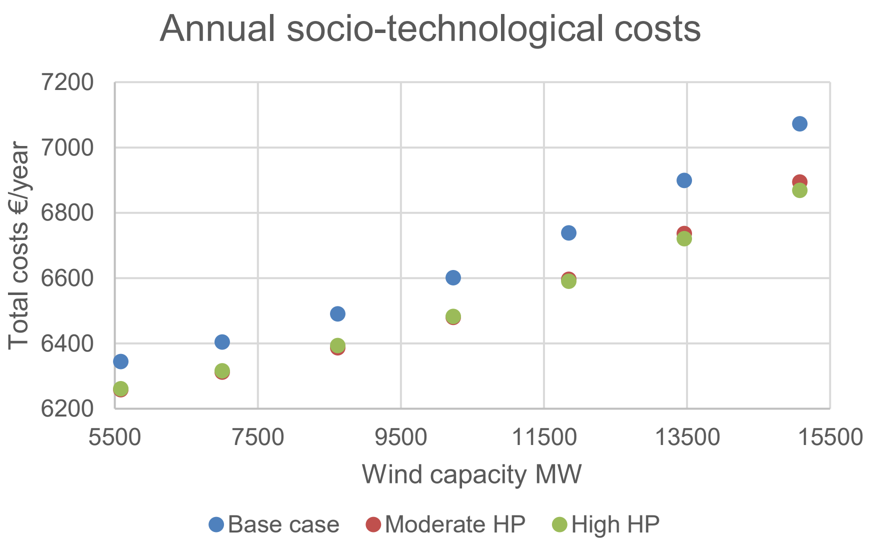
  = Electricity production that cannot be used or exported

- Annual costs as well as fuel usage show a decrease with increasing HP capacity.



Figures: Results from Finnish energy system model; Critical excess electricity production, annual fuel usage and annual socio-technological costs.





Task 3.2: Conclusions

- Heat pumps in the district heating sector can help to integrate weather-dependent renewable electricity into the grid cost-effectively in Finland.
- Also, availability of renewable electricity is in key role in utilizing heat pumps.
- Additional heat production methods, such as CHP and heat only boilers, are needed for high district heating demand periods in addition to low wind production periods.
- More research is needed on the role of large-scale heat storages and combination of HP and electric boilers.

WP 3: Publications and Theses

- Conference paper: Economic optimization and global sensitivity analysis of power-to-heat systems in a small district heating network: a case study https://doi.org/10.52202/077185-0047
- Master thesis: Large-scale heat pumps in energy system: the role in decarbonization of district heat production and balancing energy production. https://urn.fi/URN:NBN:fi-fe2025051240273

Work package 4: Market Needs and New Business Models

WP 4: Market Needs and New Business Models

- Objective: Identify and enable business opportunities for next-gen heat pump (HTHP) technologies through ecosystem modeling, commercialization strategies, and international scalability.
- Ecosystem Focus: Modeled Finnish and Nordic industrial heat pump business ecosystems; highlighted dependencies, value streams, and actors driving transformation.
- Commercialization Tools: Developed course-based commercialization roadmaps; proposed five scenarios for HTHP diffusion leveraging theoretical frameworks.
- Market Research: Conducted surveys and B2B interviews in Finland and Sweden to map HTHP adoption trends and market readiness.
- Theoretical Contributions: Published insights on innovation diffusion, institutional pressures, and consumer preferences in high-temperature energy solutions.

Task 4.1: description and objectives

- Goal: Model the industrial heat pump business ecosystem to reveal actor relationships, value flows, and key transformation drivers
- Focus Areas:
  - Understand international and Finnish market dynamics in the HTHP sector.
  - Map value networks and actor interdependencies in the ecosystem.
- Scope:
  - Identify opportunities for innovation and commercialization across the value chain.
  - Evaluate competitive positioning and strategic gaps for ecosystem players.
- Strategic Objective: Enable firms to align with evolving energy system requirements and capitalize on the shift toward electrified heating.
- Methodology: Combined literature-based modeling, industry insights, and collaborative partner input to build a structured ecosystem view.
- Intended Impact: Provide an evidence-based toolset to guide strategic business development and policy alignment in heat pump markets.

Task 4.1: Survey research

- Purpose: To collect market data on high-temperature heat pump (HTHP) development, particularly focusing on Finland and Sweden.
- Design Process:
  - A structured web-based survey was developed.
  - Followed by B2B telephone interviews to deepen insights.
  - Survey aimed to assess trends, technologies, and adoption drivers.
- Execution:
  - The task was outsourced to Feelback Oy (GoOn) through a small procurement procedure.
  - Translation services included to support data collection in local languages.
- Cost & Vendor:
  - Total cost: €22,865.59 (incl. VAT).
  - Selection based on best price/quality offer from two bidders
  - Final expense based on the number of survey responses and interviews.
- Outcomes:
  - Survey results formed the basis for identifying key drivers and barriers in the adoption of HTHP technologies in the Nordic market.

Task 4.1: Results

- Mapped Industrial HTHP Ecosystem: Defined key actors, interdependencies, and value flows in the Finnish and Nordic heat pump markets
- .Identified Market Drivers and Barriers: Survey and qualitative research confirmed economic feasibility, trialability, and observability as critical enablers of adoption
- Data-Driven Market Insights: B2B survey across Finland and Sweden (n=191); key sectors: dairy, beverages, pulp & paper; confirmed gaps in awareness,and institutional readiness
- Theoretical Contributions: Developed institutional pressure and innovation diffusion models linking technology uncertainty and adoption intention.

Task 4.1: Conclusions

- [Industry] Clear Value Network Identification: Mapping of the HTHP ecosystem reveals critical interdependencies and highlights the need for coordinated strategies across manufacturers, utilities, and policymakers to enable scalable adoption.
- [Industry] Trialability and Observability Drive Adoption: Firms prioritize technologies that are demonstrably tested and easy to observe in real use—pilots and references are essential tools for industrial scaling.
- [Theory] Institutional Pressures Shape Adoption Intent: Regulatory norms and perceived legitimacy are major theoretical constructs influencing energy-efficient technology diffusion in supply chains
- [Theory] Innovation Diffusion Requires Contextual Moderators: Knowledge and technological familiarity significantly moderate the impact of core innovation diffusion variables like trialability and observability on adoption outcomes.

Task 4.2: description and objectives

- Objective: Identify commercialization paths and design innovative business models for the industrial heat pump (HTHP) ecosystem
- Scope:
  - Explore how technological innovations and new combinations can accelerate time-to-market.
  - Investigate ecosystem-level business models to capture added value across stakeholders.
- Key Aims:
  - Evaluate existing business models and generate new ones tailored to HTHP solutions.
  - Shorten commercialization cycles and support faster deployment of clean heating technologies.
- Approach:
  - Engage industry partners in workshops and interviews to co-develop scalable business scenarios.
  - Use insights from WP1–WP3 (tech development, process integration, market dynamics) to refine model design.
- Strategic Intent: Equip stakeholders with practical frameworks to navigate and capitalize on the energy transition.

Task 4.2: Results

- Scenario-Based Commercialization Models: Developed five commercialization roadmaps for HTHP integration through a consulting course format, incorporating theoretical and stakeholder inputs.
- Student-Led Ideation Framework: Facilitated project-affiliated course where students designed stakeholder-informed scenarios addressing market entry, ROI models, and scaling options.
- Shift Toward Theory-Driven Design: Refined project goals to align with research strengths; emphasized systems thinking and green innovation ecosystem frameworks as foundations for model creation.
- Workshop and Course-Based Outputs: Leveraged case-based teaching to guide business model development; addressed commercialization bottlenecks like stakeholder alignment, funding gaps, and product-market fit.

Task 4.2: Conclusions

- [Industry] Customization Enables Faster Market Entry: Flexible commercialization scenarios tailored to different ecosystem actors (e.g., utilities, tech developers) reduce time-to-market and improve alignment with stakeholder capabilities
- [Theory] Systems Thinking Enhances Commercialization Research: Integrating systems theory into commercialization planning reveals dynamic relationships between ecosystem actors, creating a richer framework for strategic diffusion analysis

Task 4.3: description and objectives

- Objective: Understand international scaling of industrial heat pump (HTHP) technologies
- Strategic Focus:
  - Analyze structural challenges and enablers for international growth in green heating markets.
  - Formulate ecosystem collaboration models that support scalable deployment.
- Key Goals:
  - Understand operational requirements for rapid scale-up of HTHP technologies across borders.
  - Identify metrics to evaluate readiness and maturity for global expansion.
- Approach:
  - Leverage insights from ecosystem modeling and commercialization planning.
  - Collaborate with industry partners and academic networks to align scaling strategies with actual market conditions.

Task 4.3: Results

- Scaling Barriers Identified: Analyzed institutional pressures, regulatory complexity, and market fragmentation as key barriers to international HTHP adoption.
- Theoretical Framework for Scaling: Developed a systems and ecosystem-based theoretical model to guide strategic decisions on global HTHP diffusio.
- Cross-Border Stakeholder Engagement: Leveraged industry input from Finland, Sweden, and academic exchange with Stockholm School of Economics to validate scaling assumptions.
- Strategic Use of Institutional Pressures: Demonstrated how institutional drivers (e.g., regulatory norms, technology legitimacy) can be turned into competitive advantages in international markets.

Task 4.3: Conclusions

- [Industry] Ecosystem Readiness Determines Scaling Success: Firms expanding internationally must align with local regulatory frameworks, institutional norms, and ecosystem maturity to reduce friction and ensure acceptance.
- [Theory] Institutional Theory Supports Global Diffusion Models: Institutional pressures (normative, coercive, mimetic) are essential theoretical lenses to explain how and why HTHP technologies succeed in international contexts.

WP 4: Publications and Theses

- Salihu, D., Immonen, M., Hallikas, J. and Sidorenko, A., 2024. Unveiling consumer preferences in household energy concepts – A conjoint analysis approach. Presented at the 14th EDSI Annual Conference 2024
- Salihu, D., Immonen, M. and Treves, L., 2025. Exploring the diffusion of energy-efficient technological innovations for decarbonizing supply chain operations. Presented at the IPSERA 2025 Annual Conference
- Salihu, D. and Immonen, M., 2025. Institutional pressures and their role in technology adoption and diffusion in energy-intensive supply chains. To be presented at the EurOMA 2025 Conference
- Sidorenko, A., Pynnönen M., Treves L., 2024. From Concept to Action: Framing Green Innovation Ecosystem. XXXV ISPIM Innovation Conference, 2024 (June 2024)
- Laine, I. Sidorenko, A., Jarrar, H., and Hachard, V., 2025. Boosting Technology Commercialisation: An Educational Case-Based Workshop for Engineering-Business Collaboration. International Journal of Technology Transfer and Commercialisation

WP 4: Seminars

- System thinking approach to green ecosystem innovation, System Thinking in Marketing Seminar in Stockholm School of Economics (June 2024)
- Case Approach in Teaching for Project Commercialisation, NEXTHEPS-project final seminar. (April 2025)
- Platform (INERCOM) Research Seminar: Housing Energy Concepts & Markets (October 2024)
- LBS Research Seminar Presentation: "Industrial high-temperature Heat Pump Diffusion in Manufacturing Supply Chains“ (November 2024)

Work package 5: Coordination, national and international networking

WP 5: Coordination, national and international networking

- The objectives of this work package were:
  - Project coordination
  - Dissemination and communication
  - To build collaborative networks and liaisons for future international cooperation
  - Screen and utilize Horizon Europe and other EU funding opportunities.

- Several internal meetings and topical workshops within the consortium were arranged during the project.

- Dissemination and communication was carried out through conference and seminar presentations, scientific publications, press releases and project webpages: https://www.lut.fi/en/projects/development-next-generation-large-scale-heat-pump-systems-nextheps

WP 5: Open seminars related to high-temperature heat pumps

- Two open seminars related to high temperature and industrial heat pumps were organized during the project
- Both seminars included presentations from both industry and academia
- 1st seminar was organized at Lahti 16.11.2023 (71 enrolled participants)
- 2nd seminar was organized at Lappeenranta 10.-11.4.2025 (105 enrolled participants including in person and online participation)

WP 5: Survey on large scale heat pump R&D infrastructure in Finland

- A survey was conducted especially focusing on high-temperature and large-scale heat pump R&D infrastructure in Finland.
- The aim of the survey was to identify existing R&D infrastructure in Finland and also to recognize the future development needs.
- The survey was carried out autumn 2024 – spring 2025 and the survey was targeted for manufacturers of large-scale heat pumps and component manufactures as well as for research institutes active in this field.
- In total the questions were sent to 8 Finnish companies or to 3 Finnish research institutes. In total 5 responses for the survey were received.

WP 5: Survey on large scale heat pump R&D infrastructure in Finland

- Due to rather small size of the Finnish heat pump industry and small number of key actors in this field, it is difficult to form a clear and comprehensive summary of the most important development needs based on the received answers. Nevertheless, some trends were observed:
  - There exists already heat pump infrastructure in Finland for testing full heat pump cycles and their main components.
  - There are new test rigs commissioned recently or will be commissioned in the near future both in companies and research institutes, further improving the heat pump testing capabilities in Finland.
  - Most of the heat pump test rigs in Finland are for rather small scales but there are some infrastructures also for several hundreds of kW to MW scale heat pumps and especially for testing their main components individually. However, it is difficult to currently test multi-MW scale systems due to the lack of very large-scale testing infrastructure (lack of infrastructure in the whole Europe).
  - New testing infrastructure is currently being realized, especially to study systems using natural refrigerants (hydrocarbons, CO_2 and ammonia) and for larger temperature lifts.
  - There would be also a need for accredited laboratories in Finland fulfilling for example standard EN14511 and European certificates (EHPA QL, CEN keymark)

WP 5: IEA Annex 58

- International collaboration was done mainly through the IEA Annex 58 collaboration program and networks, including company and academic participants from 14 partner countries.
- The Annex 58 concentrated on high temperature heat pump technology including the following reports:
  - Task 1: Technologies – State of the art and ongoing developments for systems and components – **Task 1 Report**
  - Task 2: Concepts – Development of best practices for promising application areas **Task 2 report**
  - Task 3: Applications – Strategies for the conversion to HTHP-based process heat supply **Task 3 report**
  - Task 4: Definition and testing of HP specifications – Recommendations for defining and testing of specifications for high-temperature heat pumps in commercial projects Task 4 report **Task 4 report**

WP5: other collaboration and seminars

- Collaboration and knowledge exchange with other research projects including:
  - High-Speed Turbomachine Technology for Industrial Heat Pumps (HiPerHP), funder Research Council of Finland
  - Development of New High Temperature Heat Pump Compressor (HT-COMP), funder Business Finland
  - Supercritical flow and heat transfer in energy conversion processes, funder Research Council of Finland

- A 3 month research visit to Leibniz University Hannover, related to the heat collector frosting studies in WP1. The visit was funded from EULiST program https://eulist.university/

- Presentations on high-temperature heat pumps and NEXTHEPS-project results in seminars, including:
  - Presentations in 10 scientific conferences (more details given in the list of publications)
  - IEA annex 58 meeting in Denmark 2023
  - Lämpöpumppupäivä (seminar organized by Finnish heat pump association)
  - Uutta energiatehokkuuteen 2025 (seminar organized by Motiva)
  - High speed day 2025

- LUT participated in international funding calls as a partner in international consortiums, including EIC Pathfinder Cooling challenge and Eurostars-funding calls. In these proposals, research findings and knowledge gained in the NEXTHEPS-project were utilized.

Summary of NEXTHEPS-project publications and theses

- 5 Journal publications
- 10 conference publications
- 4 Master theses related to the project

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