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Report

Site approval test of heat pump drying

Design, installation, and test run with of demonstration unit

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ABSTRACT

Demonstration unit for heat pump drying

The objective of the *SusOrgPlus* project is to prototype and validate the concept of heat pump drying at TRL 6 in close cooperation with the supply industry. The demonstration unit shall be used to maximise energy efficiency and simultaneously increase the product quality.
This report documents the activities towards the building and installation of the demonstration unit as well as the site approval tests. The system consists of an industrial convective drying unit (supplier Innotech GmbH, Germany), a heat pump with R744 as working media including 2 thermal storage tanks (supplier Cadio AS, Norway) and a Data Acquisition System (supplied by SINTEF). The dryer was installed in the *HighEFFlab* of SINTEF in July 2019 and the heat pump integrated in the following month. Final site acceptance tests were done in November 2019 and concluded the Task 2.2 of the *SusOrgPlus* project.
The installation was financed by the Infrastructure project *HighEFFlab* and will be available for R&D until 2028.

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APPENDICES

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1 Background

Drying is a thermal dehydration method and is one of the most frequently used preservation methods for foods and other materials. In consideration of increasing fossil fuel depletion and environmental pollution, it should be evaluated how the process can be decarbonized. The main energy source are still fossil fuels, and the depletion of fossil fuels harbours a future risk for energy shortages. Furthermore, fossil fuel consumption is a large cause for climate gas emissions. It is therefore necessary to develop drying systems that are independent of fossil fuels and can be integrated the renewable energy grid. By the correct integration of heat pumps (with or without thermal storage) the primary energy consumption can be reduced so that the process becomes less energy intensive.

The most common used drying technology in the industry is convective drying [1]. The water content of the product is reduced by a flow of hot air as drying agent, resulting in an extended shelf life compared to fresh products. This drying process is widely used in all kind of industries and is a highly energy-intensive process. It is estimated that around 10 – 20 % of the total energy used in all industries in developed countries is used in drying processes, whereas the major amounts are demanded by the food and paper industries [2,3]. Especially in the food processing sector, which generally has high quality requirements for dried products, the thermal efficiency is often relatively low in the range of 25 – 50 % [4]. Typically, batch dryers are used for small and medium production runs and for relatively thin products like fruits or vegetables [5]. Food is loaded onto trays in a cabinet and left until the drying process is complete. Due to the simple design, cabinet dryers usually have limited turnover rates and the drying process is not uniform throughout the drying space.

The basic advantages of heat pump driven convective drying results from the ability to recover energy from the already used drying air and reuse it in the process. This results in high values for the specific moisture extraction ratio (SMER), often between 1 – 4 kg of evaporated water per 1 kWh, since heat is being recovered from the moist air [6]. This can result in a drying efficiency of up to 95 % compared to 30 – 40 % for other hot air drying methods [7].

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[1] J. C. Atuonwu, X. Jin, G. van Straten, H. C. v. Deventer Antonius, J. B. van Boxtel, Reducing energy consumption in food drying: Opportunities in desiccant adsorption and other dehumidification strategies, Procedia Food Science, p.1799-1805. doi:https://doi.org/10.1016/j.profoo.2011.09.264, 2011

[2] C. Strumillo, P.L. Jones, R. Żyłła, Energy Aspects in Drying. Handbook of Industrial Drying. 1075-1101. 10.1201/b17208-59, 2014

[3] T. Kudra, Energy aspects in drying. Drying Technology 22(5), p. 917–932, 2004

[4] A. S. Mujumdar, Handbook of Industrial Drying, 3rd Ed; CRC Press: Boca Raton, FL, 2006

[5] W. L. Kerr, Chapter 12 - Food Drying and Evaporation Processing Operations, Handbook of Farm, Dairy and Food Machinery Engineering (Second Edition), Academic Press, p. 317-354, 2013

[6] S.K. Chou, C. Kiang, Jon, 47 Heat Pump Drying Systems: Handbook of Industrial Drying, Fourth Edition. 10.1201/9781420017618.ch47, 2006

[7] C. O. Perera, M. S. Rahman, Heat pump dehumidifier drying of food. Trends in Food Science & Technology, 8(3), 75-79. doi:https://doi.org/10.1016/S0924-2244(97)01013-3, 1997

Industrial heat pumps with a heat sink of up to 100 °C using natural refrigerants like R717, R718 or R744 are already conventionally established. This makes heat pumps very well suited for food drying, which is usually performed at temperature levels of up to 70 °C. The natural refrigerant R744 is an environmentally friendly alternative to common heat pump refrigerants. It offers a global warming potential of 1 and it is not flammable. No restrictions regarding the utilization are existent or planned. R744 as refrigerant in heat pump dryer systems for the food industry is evaluated to give better performance than classical refrigerants like R134a, but with higher irreversibility of the expansion device [8], [9]. The system performance of a R744 heat pump drying system yields large potential for utilization in different industries.

While the general potential of heat pump drying is evaluated in literature the technology is not taken up by the industry in larger scale. The reasons for this are several and can be summarized as follows:

1. The system integration between drying system and heat pump is difficult to optimize since a balance between the drying conditions and the heat pump operations must be found. The heat pump performance is influenced by the drier design and drying conditions and the heat pump can potentially limit the operational envelop of the dryer. Therefore, most supplier for drying equipment do not offer heat pump drier as standard solutions. Suppliers of heat pump on the other hand are lacking the necessary background to design a flexible heat pump solution which fits to industrial drying system.
2. Fossil fuel is for many European processing industries still the most economic and flexible alternative for the generation of process heat. Heat pump system are depending on electricity as energy source and even with reduced primary energy consumption the difference (between fossil fuel and electricity prices) cannot be covered. Therefore, electrified drying system are often not considered as realistic option.
3. The system complexity of a heat pump dryer is increased (compare to a conventional drier) and the processing industry is reluctant to "change a running system".
4. There is a lack of best practice and industrial demonstration units which can be used to investigate the concept on a high technological readiness level (TRL). Even if the concept is working "on paper" it is difficult for the industry to transfer (or even see) how this theoretical concept can be taken up in their production facility, especially since there is no supplier for "heat pump driers".

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[8] M. Bantle, K. H. Kvalsvik, I. Tolstorebrov, Performance simulation of a heat pump drying system using R744 as refrigerant, Proceedings of the 12th IIR Gustav Lorentzen Conference on Natural Refrigerants GL2016, Edinburgh, UK, 2016

[9] J. Sarkar, S. Bhattacharyya, M. Ramgopal, Carbon dioxide based heat pump dryer in food industry, International Conference on Emerging Technologies in Agricultural Food Engineering, December 2004, IIT Kharagpur, India, 2004

The above points are also discussed in the white paper on "Strengthening industrial heat pump innovations" [10].

The aim of the demonstration unit for the SusOrgPlus project is therefore as follows:

(a) Demonstrate the technical feasibility of heat pump drying on the TRL 6: "technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)" according to [11], hereby enabling climate neutral convective drying (overall aim).

(b) Validate the concept of heat pump drying in detail in an industrial relevant size, enabling hereby industrial uptake and upscaling

(c) Establish a demonstration unit that can be used for future R&D in order to reduce the gap between heat pump manufacturer and suppliers of drying equipment.

(d) Phase in of natural refrigerants, which are required also with respect to the F-gas regulation [12] and are not banned or limited in future heat pump applications.

[10] White Paper "Strengthening Industrial Heat pump Innovation – Decarbonizing Industrial Heat", 2020 https://www.sintef.no/globalassets/sintef-energi/industrial-heat-pump-whitepaper/2020-07-10-whitepaper-ihp--a4.pdf/

[11] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

[12] https://ec.europa.eu/clima/policies/f-gas/legislation_en

2 Design of the Heat pump drier

The aim of the investigations was to validate a heat pump drying system (for organic products such as apples) in a relevant environment. The size and capacity of the drier will in this case define if the investigation is relevant. The project partner Innotech Ingenieursgesellschaft GmbH (Germany) supplies convective drying systems and in agreement with them it was decided to use the conventional drying size of their cabinet dryer "Hohenheim HT8". This is an industrial cabinet dryer with a product capacity of 100 kg per batch. The thermal capacity is normally between 20 and 40 kW, however in most cases 20 kW is a sufficient supply of process heat, since only products which would dry very fast would require a higher capacity in the beginning of the batch operation. For the planned drying tests with organic apples (100 kg per batch) the capacity will be sufficient; at the same time it will be possible to use the dryer for other products. It was decided that the subsequent design and specifications will be done one for this cabinet dryer (HT8).

2.1 Cabinet dryer HT8

The design of the modified drying cabinet HT8 s shown in Figure 1. The following modification where discussed and implemented by Innotech:

- Additional heat exchanger for dehumidifying the drying air (heat exchanger "cold"), working media water
- Additional heat exchanger for heating the drying air from by the heat pump (heat exchanger "heat"), working media water
- Additional air flaps to operate the drier in heat pump mode, conventional mode and in bypass modes between.
- Control system: possibility for humidity control, reduced air flow, as well as regulation of mass flow of heating and cooling.

The design of the system was estimated on heat pump size of 10 kW refrigeration (cold). The boundary connections to the heat pump will be through the heat exchanger. The design and the operational modes are described in more details in an open access article [13].

The design and construction of the modified cabinet dryer "Hohenheim HT8" was done by Innotech.

[13] https://www.sciencedirect.com/science/article/pii/S2451904920300937

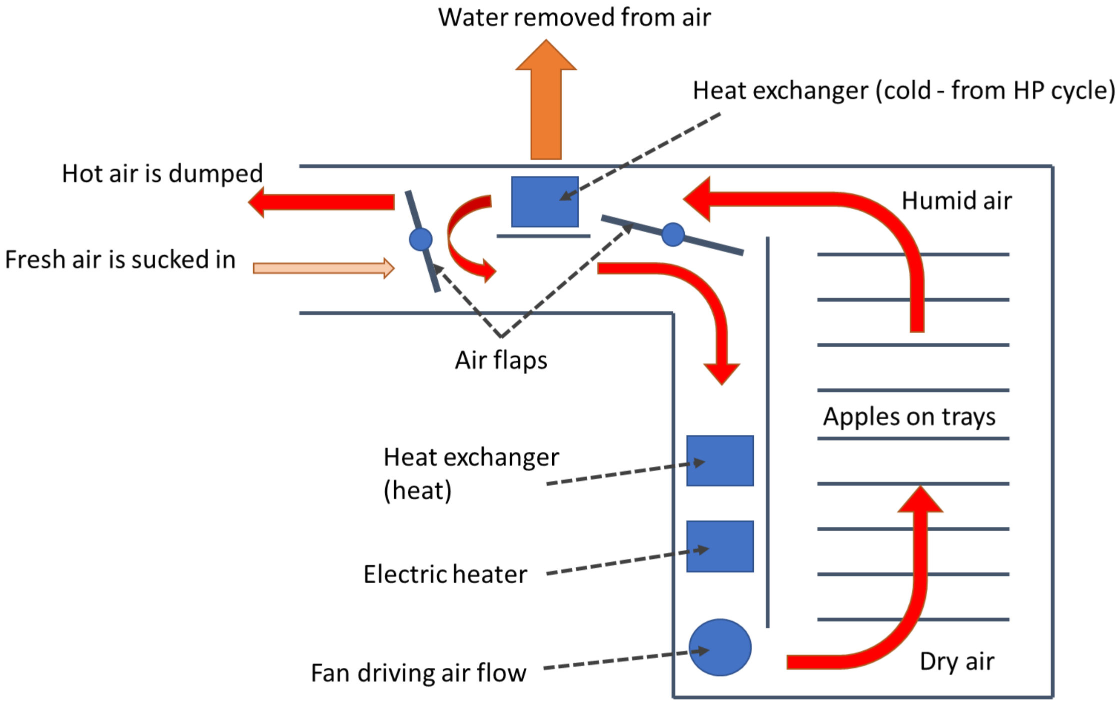

Figure 1 Schematic of the modified drying cabinet "Hohenheim HT8"

2.2 Heat pump with R744 as working media

For the heat pump design the expected performance of the dryer cabinet is on of the main design criteria. The dryer cabinet is operated as batch dryer and the available waste heat as well as the energy demand will depend on the drying rate (see Figure 2). For a continuous drier operation, the heat pump system can be designed for a fixed capacity as long as a operation of the dryer results in a constant drying rate. The drying rate can change depending on the product or its moisture content as well as the drying conditions (mostly temperature).

For a batch operation the drying rate will be high in the beginning and lower to almost zero in the end of the process. Further variations can also be expected depending on the product or its moisture content as well as the drying conditions (as in continuous operation). The design of the heat pump most thus, cover a wide operational area which requires more flexibility.

It is, however, the nature of heat pumps that they have an optimum thermodynamic efficiency at a constant operation point. Large variations in the availability of waste heat or heat capacity demand will decrease the efficiency to a point at which the system cannot be operated any more.

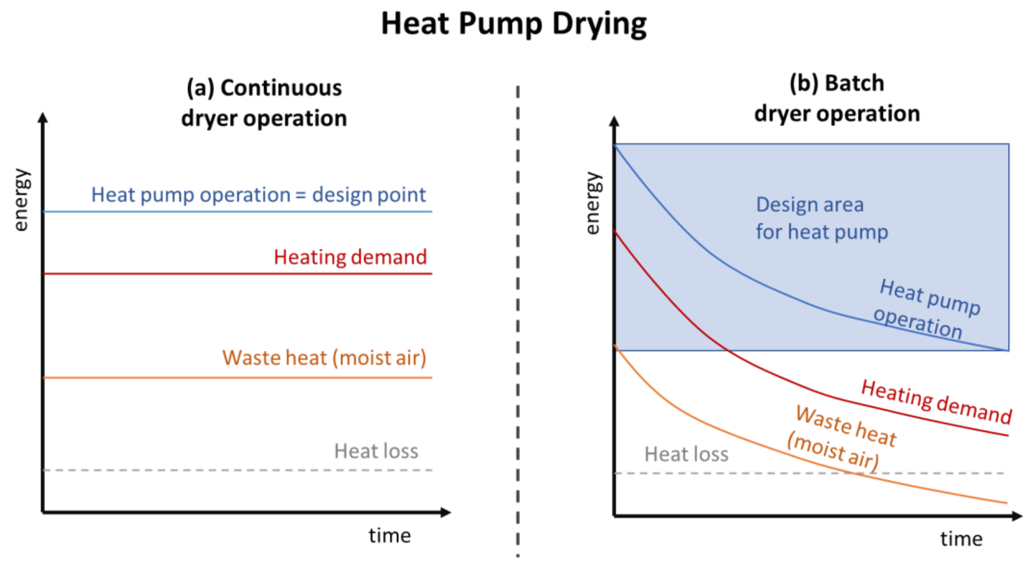

Figure 2: Continuous and batch wise dryer operation and their influence on the heat pump design (principal sketch).

For the heat pump design the above consideration must be taken into account in order to specify the system and its intended operation. One of the most common mistakes is over-dimensioning of the heat pump system which will result in a less efficient operation (illustrated in Figure 3).

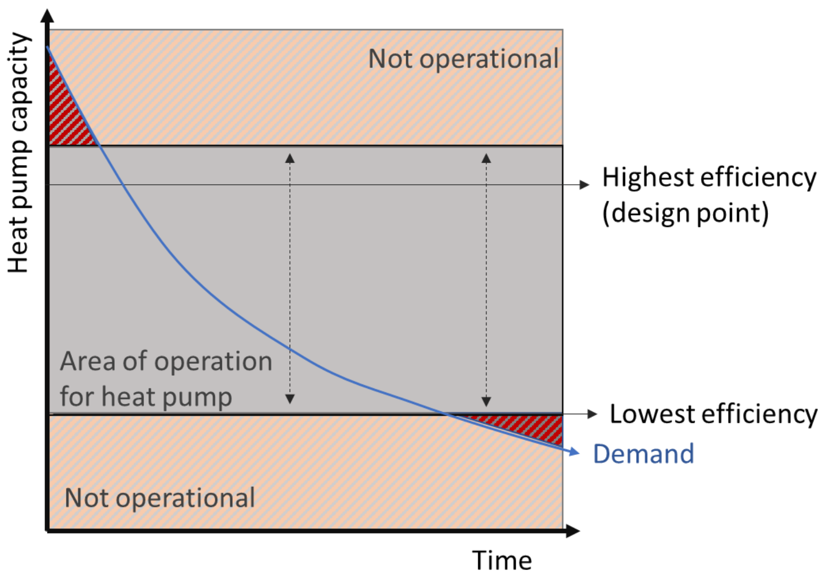

Figure 3: Simplified operational envelop for heat pumps

For the demonstration unit, the following specifications and design conditions where specified under the above discussed operation:

- The heat pump should cover a wide operational envelop of a batch dryer and the capacity should be regulated as much as possible. Therefore, a more efficient capacity regulation by frequency converter must be included for the compressor.
- The capacity should cover 15-25 kW at the evaporator side (=expected drying rate of 20 l/h in average).
- The heating capacity should cover 20-35 kW and should be able to substitute the electric heater completely.
- The heat pump should use a natural refrigerant (low global warming potential) which can operate between 4°C and 70°C. The safety class should be A1 (non-toxic, non-burnable), since the heat pump will be placed in a production site or laboratory. A screening of possible refrigerant concluded that R744 will fulfil this requirement.
- Water will be used as secondary heat transfer media between the heat pump and the dryer. This also allows to use standard heat exchanger in the systems (R744-water HX in heat pump, water-air HX in dryer)
- Two thermal storage tanks (100-200 litre) need to be integrated in the heat pump system in order enable dryer operation outside the operational envelop of the heat pump (red areas in Figure 3).

The principal sketch of the heat pump system and it's system integration is illustrated in Figure 4.

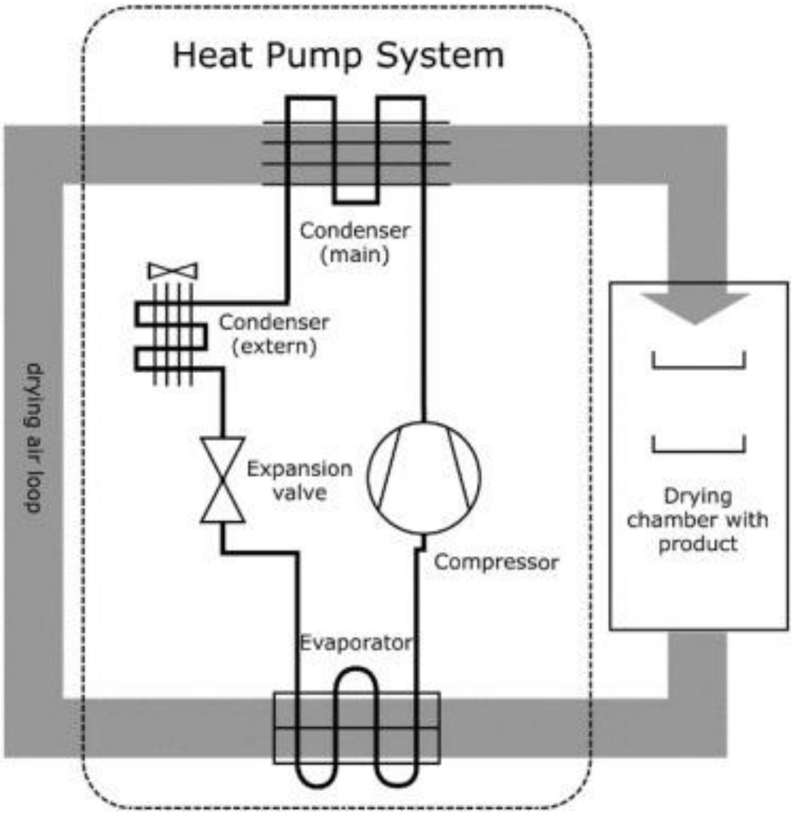

Figure 4: Heat pump with working fluid R744 with its main components in heat pump drying.

2.3 Data Acquisition System (DAQ)

The main aim of the investigation is to document the energy consumption of the dryer with a heat pump. In the assessment of heat pumps, the most used performance parameter is the Coefficient of Performance (COP). The COP of a heating system is

$$COP_{HP} = \frac{Q_H}{W}, \qquad (1)$$

where Q_H [kW] is the heat delivered by the heat pump and W [kW] is the total energy consumption. The total energy consumption for the one-stage compression heat pump cycle is

$$W = W_{\text{compr}}, \qquad (2)$$

where W_{compr} is the work input to the heat pump compressor.

The COP of a heat pump used in a drying process also includes the total energy consumption of the secondary installations and is determined as follows:

$$COP_{\text{HPD}} = \frac{Q_{cond}}{W_{\text{tot}}}, \qquad (3)$$

where Q_{cond} [kW] is the heat delivered at the condenser and W_{tot} [kW] is the total energy consumption for the heat pump dryer. The total energy consumption is given by

$$W_{\text{tot}} = W_{\text{compr}} + W_{\text{fan}} + W_{\text{pumps}} \tag{4}$$

where W_{compr} is the work input to the heat pump compressor(s), W_{fan} is the work input to the additional fan/blower unit needed to provide a certain velocity to the drying agent (air/steam) and W_{pumps} is the work input to the additionally needed pumps of e.g. secondary installations.

For the drying process, we define the thermal efficiency η_{thermal} [kg water/kJ] as

$$\eta_{\text{thermal}} = \frac{\Delta x}{\Delta h}, \tag{5}$$

where Δx [kg] is the amount of removed water from the product and Δh [kJ] is the amount of energy consumed. Here, for the heat pump dryer system, Δh equals heat delivered at the condenser, *i.e.*, $\Delta h = Q_{\text{cond}}$.

A commonly used performance parameter for the combined heat pump dryer system is the Specific Moisture Extraction Rate (SMER). The SMER number [kg/kWh] is defined as the product of the heat pump COP and the thermal efficiency η_{thermal}, that is,

$$SMER = COP_{\text{HPD}} \cdot \eta_{\text{thermal}} \,. \tag{6}$$

Using the relation $\Delta h = Q_{\text{cond}}$, we find that

$$SMER = \frac{\Delta x}{W_{\text{tot}}}, \tag{7}$$

and, hence, the SMER is defined as the mass [kg] of removed water from the product divided by the required energy [kWh] for this. In other words, the SMER gives a key specification of the drying efficiency of the heat pump dryer system. Alternatively, the Specific Energy Consumption (SEC), which is the reciprocal of the SMER, is used to compare the energy efficiency of various heat pump dryers. In this work we use the SEC [kWh/kg] as the key performance parameter, which is defined as

$$SEC = \frac{1}{SMER} = \frac{W_{\text{tot}}}{\Delta x}. \tag{8}$$

Hence, the SEC gives the required energy input per kg of evaporated water in the dryer. For some heat pump dryer systems, external heat is used to replace part of the work input W_{tot}. The SEC can then be expressed as

$$SEC = \frac{W_{\text{tot}} + Q_{\text{ext}}}{\Delta x}, \tag{9}$$

where $W_{\text{tot}} = \sum W_i$ is the sum of work input to the compressor, fan, pumps, etc. and Q_{ext} is the external heat input.

The DAQ is designed and installed by SINTEF and is instrumented as indicated in Figure 5. With this instrumentation it will be possible to document the above discussed KPI.

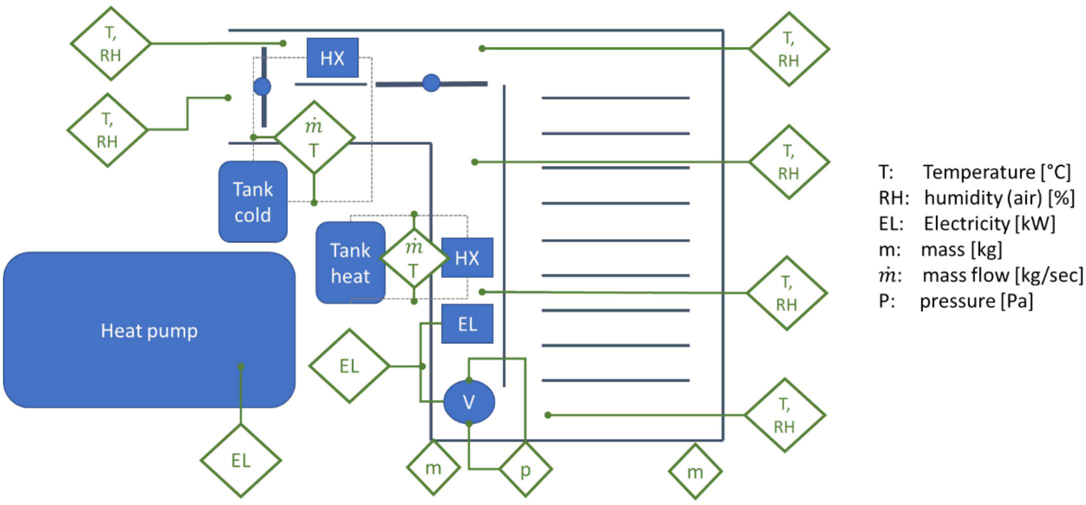

Figure 5: Sensors and measuring points for the DAQ system of the HPD

3 Installation of heat pump drying system

The tenders offers and purchase contracts for the different systems and instruments are not part of this deliverable since they are subject to confidential agreements. All purchases were done according to the approved proceedings and regulations of SINTEF Energy Research and documented accordingly.

3.1 Dryer cabinet HT8

The dryer cabinet was produced according to the discussed specifications and modifications by Innotech during spring 2019. SINTEF and Innotech performed a site acceptance tests in Germany in May 2019 with focus on uniform drying performance over all trays. For that the dryer was filled with 100 kg of sliced apples and the drying progress was evaluated on the different trays. No significant difference was documented between the 50 trays (see Figure 6).

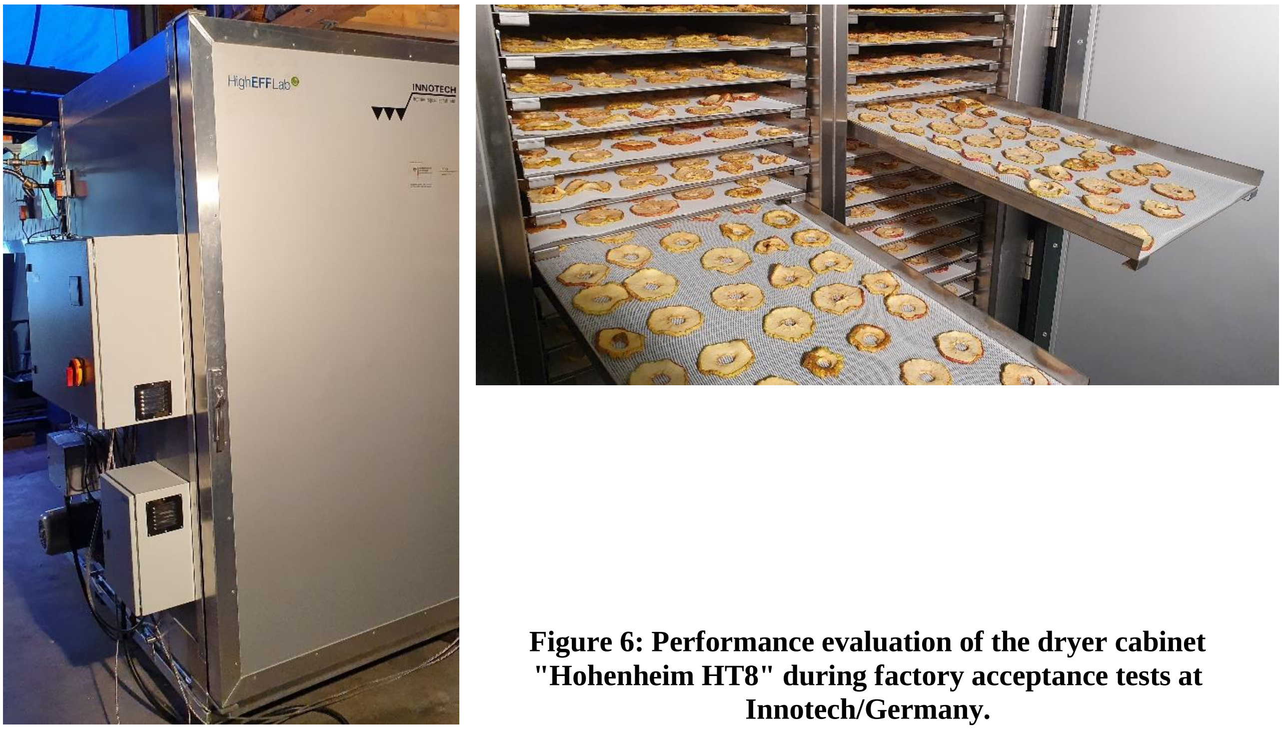

Figure 6: Performance evaluation of the dryer cabinet "Hohenheim HT8" during factory acceptance tests at Innotech/Germany.

The cabinet dryer was then shipped to Trondheim/Norway where SINTEF took possession of and installed it in HighEFFlab (Figure 7).

Figure 7: Installed dryer cabinet in HighEFFlab at SINTEF (including framework for weight cells).

3.2 Heat pump system (including thermal storage)

The heat pump system was offered by Cadio AS (Trondheim, Norway) according to the specifications and operational parameters as specified in chapter 2. It was constructed during fall 2019 and installed in November 2019.

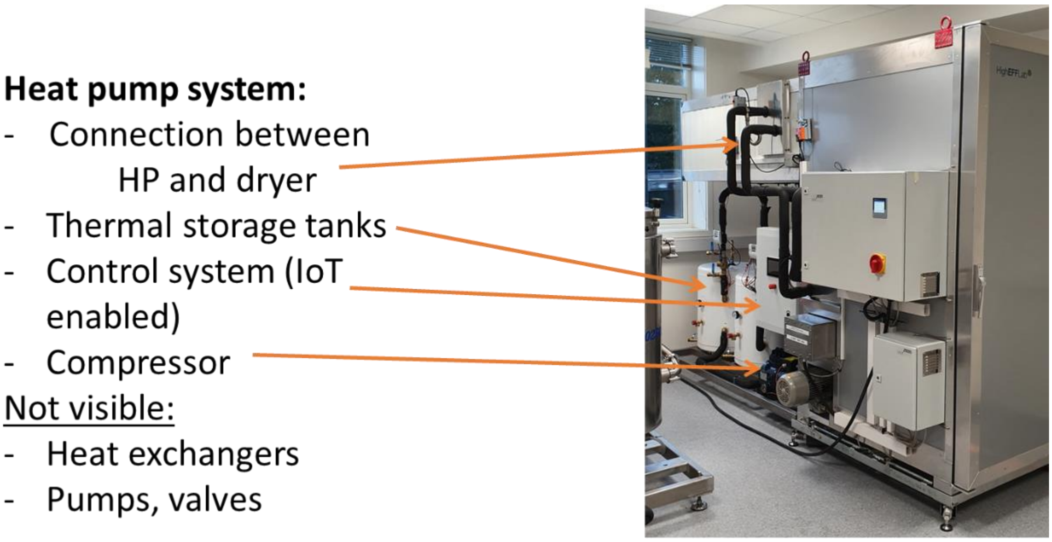

Figure 8: Heat pump fitted to the dryer (on weight cells) and ready for site acceptance tests.

The DAQ system was installed by SINTEF in the following weeks and in December 2019 the heat pump system was ready for the "Site Acceptance Tests".

4 Site Acceptance Tests

The aim of the site acceptance tests was to document the operation of the heat pump drying system in the conventional mode (heated by electric heater) and in the heat pump mode. Therefore, two acceptance tests were performed at a drying temperature of 60°C. The DAQ system was used to document the specific moisture extraction rate SMER in which most of the recorded values have an influence.

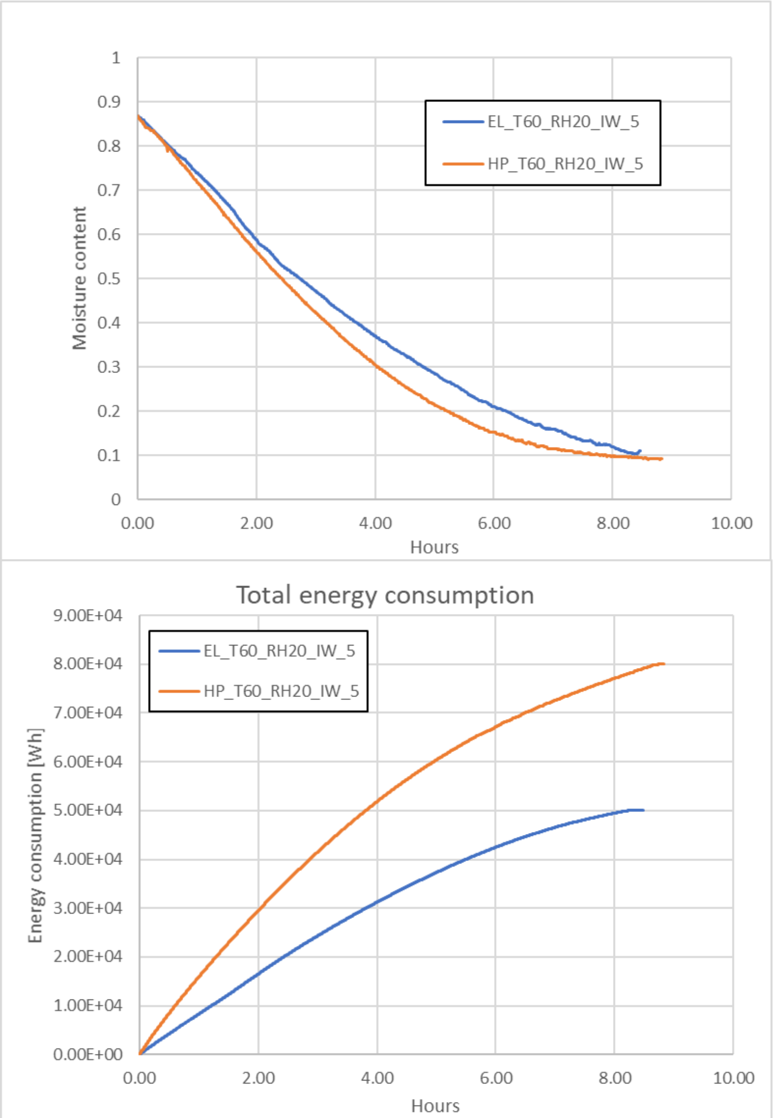

Figure 9: Moisture content and energy consumption during the site acceptance tests in heat pump (HP) and conventional (EL) mode.

In Figure 9 the two different operational modes are compared, and the documented values are used to obtain the SMER. The heat pump mode resulted in a faster drying process (1.2 hours faster) compared to the conventional mode due to the high cooling capacity of the heat pump. In both modes around 50 kg of water was removed. The energy consumption of the heat pump mode higher than the energy consumption of the conventional mode (67.5 kWh vs. 47.2 kWh) and the SMER was 0.7 kg/kWh and 1.08 kg/kWh respectively. The performance of the heat pump mode must be improved in order to document the expected potential of the concept. Optimization of the operation of the heat pump dryer will be performed in the next task and was not a part of the site acceptance tests.

It was concluded that the site acceptance tests were satisfactory and that the demonstration unit works as intended.

Further tests during 2020 have also confirmed the repeatability of the tests performed in December 2019 (see Figure 10).

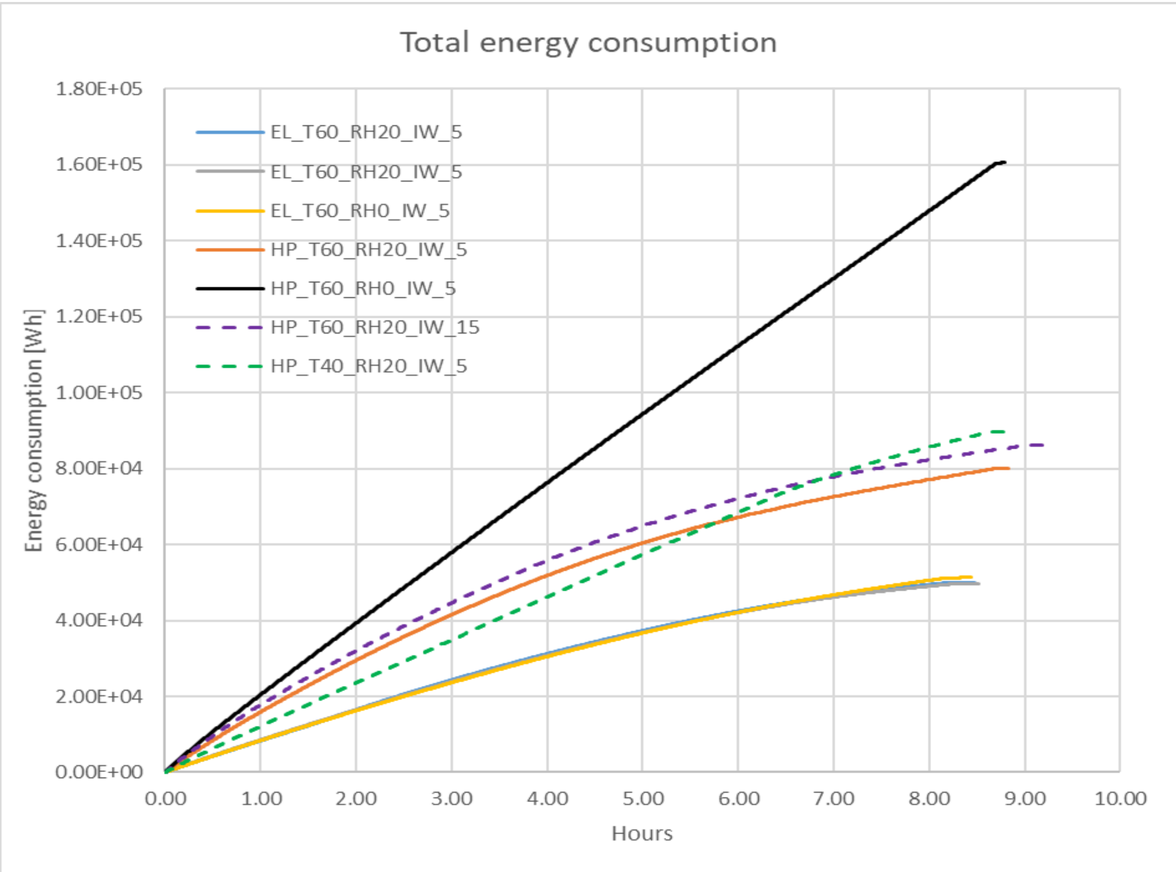

Figure 10: Repeatability of the site acceptance tests.

5 Conclusion

The aim of the project-task was to install a demonstration unit which enables to evaluate the concept of heat pump drying in an industrially relevant environment (TRL6). The design and construction activities of this task have resulted in the installation of a heat pump dryer which can be operated in conventional mode as well as heat pump mode. The determined Key Performance Indicators allow a direct comparison of the two modes. Also, the repeatability of the tests was documented.

The conclusion is therefore that the Milestone 2.1 "Heat pump drier prototype up and running" is reached and that the task 2.2 is finalized.

Further activities need to focus on optimalisation of the operation of the demonstration unit, and to disseminate the system to industry and R&D. The system is also available for further tests of the concepts, which is evaluated in work package 1 of the *SusOrgPlus* project in cooperation with university Kassel/Germany, Innotech/Germany and University Tuscia/Italy.

The demonstration unit is established in SINTEF's *HighEFFlab* and is available for other R&D.

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