CHEMICAL ENGINEERING TRANSACTIONS
VOL. 81, 2020

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

**ISBN** 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081232

# Design and Integration of Heat Recovery in Combination with Solar and Biomass-based Heating in a Drying Plant

Elin Wallin, Rickard Fornell*, Oskar Räftegård, Tommy Walfridson, Jessica Benson

RISE Research Institute of Sweden, Box 857, 50115, Borås, Sweden
Rickard.Fornell@ri.se

The EU27 annually generates 90 Mt of food waste, and approximately 40 % of this waste is generated during manufacturing. The food processing industry needs to develop improved and sustainable solutions for waste valorisation and re-use. The project DRALOD addresses this issue since it aims at design, integration and assessment of the performance of a heat recovery system in connection with an innovative low-temperature air drying unit where high moisture food waste is dewatered and sold as a by-product with preserved nutritional ingredients. The air used for drying is preheated using solar heat and a biomass boiler, and in this project the potential benefits of integration of a heat recovery system have been investigated. Due to the impurities available in the humid exhaust air from the dryer, the heat recovery is designed with two principal systems; a wet scrubber condensation system and a heat pump system. Simulations using hourly meteorological data from Madrid have been made for the total system with heat recovery, and the generated results have been used as inputs in a techno-economic analysis in order to assess the integration of the heat recovery and how sensitive different economic parameters and assumptions are for the results. It can be concluded from the assessment that the prices of electricity and biofuel will have a high impact on the economic performance and design. For the integration of the heat recovery system to be economically justifiable it is estimated, given assumptions made in this analysis, that the electricity cost needs to be less than 5 times higher than the biofuel cost.

## 1. Introduction

For sustainable use of resources, it is important to minimise waste by finding innovative uses for residual streams. In order to create value from waste streams in the food industry water often needs to be removed. Drying and evaporation are two technologies that are often used for this purpose, but they are both energy-intensive unit operations (Marechal and Muller, 2008). In comparison with most of the energy-intensive industries, such as petrochemical, paper and iron and steel production, the processing of food also requires relatively low temperature levels. As a result, the food production sites can typically integrate heat pumping or combined heat and power solutions to upgrade waste energy (Marechal and Muller, 2008). This paper is part of the project DRALOD, a Fast Track to Innovation (FTI) project devoted to deliver an innovative drying plant concept with the main aim of bringing financial feasibility to the valorisation and reuse of waste from the food processing industry. The project scope is the design, implementation and demonstration of a low-temperature air drying technology based on the combined use of renewable energy sources (solar and biomass) for air heating. The solar air heating technology implemented is the SolarWall patent protected technology, using micro-perforated metal collectors that create negative pressure in an air cavity when heated by solar radiation. A biomass heating system with high flexibility concerning type of fuels, fuel quality and mode of operation (full and part load, dynamic operation behavior) enabling low operational costs is included as an auxiliary heat source for the drying system. Finally, a heat recovery system adapted to the characteristics of the plant (high air mass flow, low drying temperature, impurities in the exhaust air used as waste heat source) is developed to increase the energy efficiency of the drying process. Compared to e.g. the systems described in (Alves-Filho, 2018) the system assessed here is not an integrated heat pump dryer, but rather a system with a specific dryer technology integrated with renewable heating in the form of solar and biomass, and with a heat recovery unit to increase the total energy efficiency. The system is similar to one of the solar thermal and heat pump systems described

Paper Received: 30/04/2020; Revised: 28/05/2020; Accepted: 01/06/2020
Please cite this article as: Wallin E., Fornell R., Räftegård O., Walfridson T., Benson J., 2020, Design and Integration of Heat Recovery in Combination with Solar and Biomass-based Heating in a Drying Plant, Chemical Engineering Transactions, 81, 1387-1392 DOI:10.3303/CET2081232

in (Grubbauer et al., 2018) although the DRALOD system is open and aims at heating ambient air, also contains a biomass boiler and operates at lower temperatures. These differences imply that there are other problems related to system performance, e.g. the variability in input conditions (temperature, humidity) and the amount of impurities in the heat source.

## 2. System description

The drying plant in this assessment is designed to dry Brewer's Spent Grains (BSG), residues from a brewery. The BSG is expected to be sold as a product used for nutraceuticals and pharmaceutical applications, which implies that the temperature in the drying process needs to be low in order to not deteriorate the quality of the BSG. The drying system is divided into four sub-systems: the solar roof, the Heat Recovery Unit (HRU), the biomass boiler and the dryer. The HRU is in turn made up of two principal systems, the wet scrubber condensation system and the heat pump system, see Figure 1. The dryer system is specified to dry above 35,000 t/y of wet BSG from 80 % wet content to 15 % wet content with 75 °C supply air temperature. In order to maintain the necessary driving force for drying, the air is not allowed to reach saturation, but will reach 85 % relative humidity.

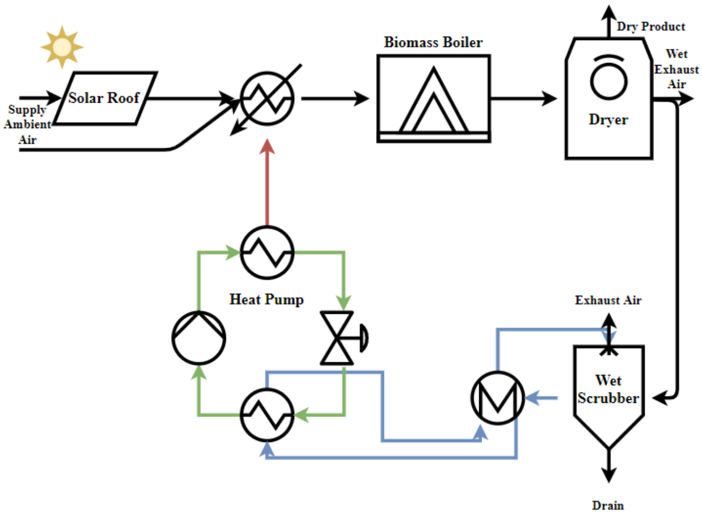


*Figure 1: Overview of the drying system and the four subsystems; Solar Roof, Biomass Boiler, Dryer and HRU (i.e. wet scrubber and Heat Pump).*

From an energy perspective this is in theory a very simple system since there are only two relevant streams to consider (since the BSG is not preheated prior to the drying plant). First the air used in the dryer needs to be heated from ambient temperature to the specified inlet temperature of supply air in the dryer (75 °C). Then the moist air leaving the dryer at 35 °C and 85 % humidity is either emitted to the atmosphere or, if an HRU is included in the system, recovered in order to preheat the supply air. Two practical problems need to be addressed in this system in order to recover the heat in the exhaust air: 1) the highly dynamic nature due to the use of ambient air for drying and the primary energy source being solar heat, and 2) the potential impurities in the exhaust air flow from the dryer. These practical issues have been addressed by using an operational strategy based on the supply of a constant volumetric air flow to the drier of 180,000 $m^3$/h. The solar heat is the first heating source in the system, and the heat pump is assumed to heat the supply air after the solar roof. Finally, the biomass boiler will heat the supply air up to 75 °C. Due to the impurities in the exhaust air a wet scrubber system, connected to a water loop where heat can be delivered to the evaporator of an ammonia-based heat pump, is included in the system. For a case without heat recovery cyclones can be used to remove the impurities. The wet scrubber system will decrease the temperature of the waste heat with a few degrees, whilst the majority of the latent heat of water in the exhaust air is condensed. The main issue to address in this system is to handle the highly dynamic nature of a drying plant by using solar heating of ambient air. This will lead to a large variation in conditions and demands a flexible operation of the system. As stated by e.g. (Schosser et al., 2019) the proper placement of a heat pump is across the Pinch point, but in practice in a system with large variation this might not be 100 % possible in practice. In Figure 2 two different operating conditions are shown, the upper curves show Pinch curves for the system when the ambient temperature is low and the sun is not shining (i.e.

cold stream (air) needs to be heated from a low temperature) and the lower curves where the temperature is higher and the solar heating is active. As seen in the upper curves in Figure 2a small amount of direct Heat Integration could in theory be possible at time points when the solar heating is not active, and the ambient temperature is low enough (e.g. winter or night time). As seen in the lower curves in Figure 2 there is no possibility for direct integration when solar heating is included in the system, and this is also the case if the ambient temperature is higher. In this study no direct integration is included due to practical reasons in the design of the heat recovery system.

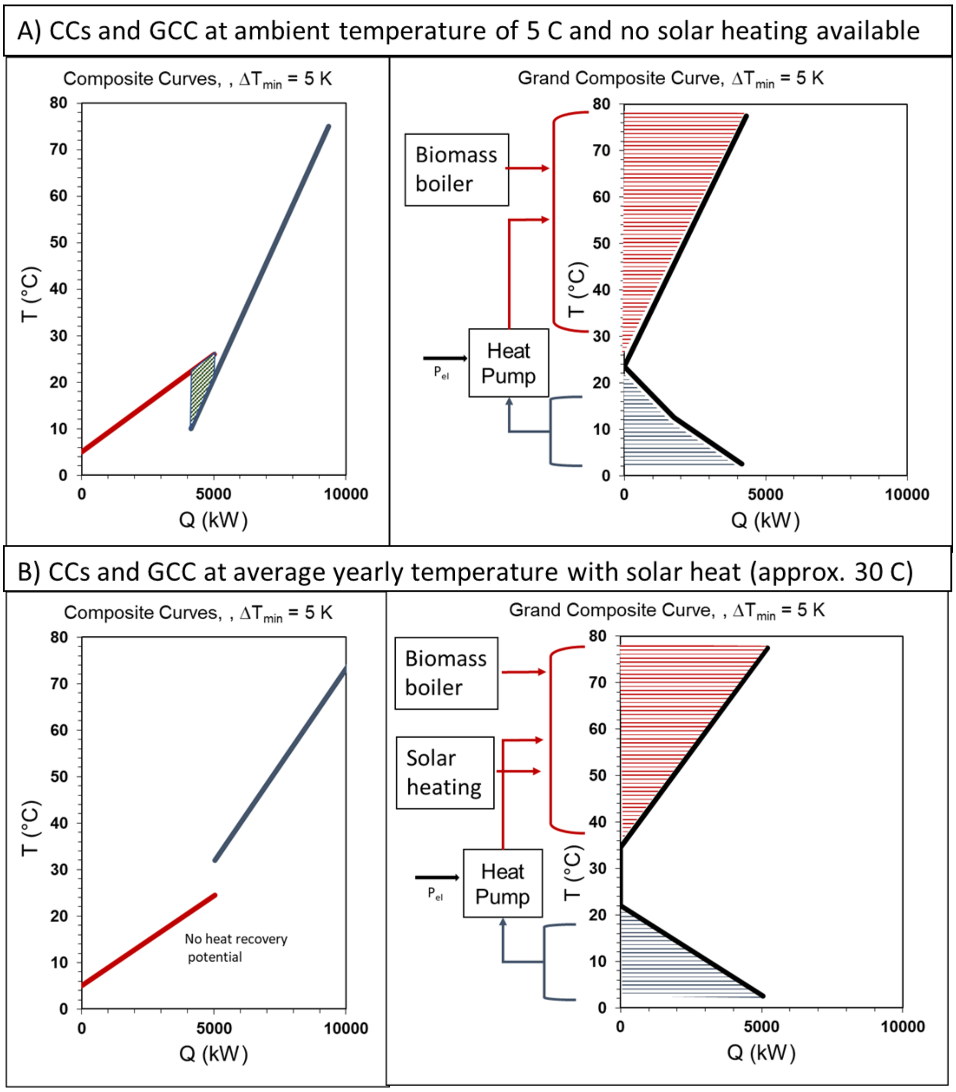


*Figure 2: Composite Curves and Grand Composite Curve of the theoretical potential of the system if solar heating is not possible and the ambient air temperature is low (A, upper two curves), and the practical potential for average ambient conditions, i.e. with some solar heating or when the ambient air temperature is high (B, lower two curves).*

## 3. Method

The drying system has been modelled in an in-house simulation model built in MS Excel, using CoolProp thermodynamic database (Bell et al., 2014) for humid air properties together with mass and energy balance calculations. Based on the modelling an assessment of the Total Lifetime Cost (TLC) for different heat recovery loads have been made. This included a future scenario analysis for the electricity and biomass prices using the Energy Price and Carbon Balance Scenarios tool ENPAC (Axelsson et al., 2018). The tool estimates the price escalation from 2025-2050 for electricity and low-graded biomass for different scenarios for European conditions. The scenario used in this paper is sustainable development (SD) as defined by the IEA in World

Energy Outlook (IEA, 2018). The values in ENPAC were compared to the 2019 values of electricity and biomass prices in Spain as stated by partners within the DRALOD project, i.e. 140 €/MWh-el and 9 €/MWh-fuel.

*Table 1: Electricity and biomass prices estimated using the tool ENPAC, with 2018 as reference year.*

| Year | Unit | Electricity Price, Sustainable Development | Low-grade Wood Fuel Price, Sustainable Development |
|---|---|---|---|
| 2018 | €/MWh | 44 | 14 |
| 2025 | €/MWh | 48 | 22 |
| 2030 | €/MWh | 48 | 31 |
| 2040 | €/MWh | 63 | 44 |

Meteonorm Timeseries (Meteotest, 2018) were used for the hourly climate data for an average year in Madrid. The data was aggregated into 79 intervals since a lot of the hourly input data were similar. By comparing the aggregated sample with the original 8,760 data points a deviation in output, as ton BSG fed to the dryer per year, between the sample and the original data set was below 2 %.

**3.1 Simulations of the dryer plant**

The drying plant system without Heat Recovery and five systems with different sizes (0.5, 1, 2, 3, 4 MW) of heat pumps were modelled and evaluated from a cost perspective by adding the yearly costs for the alternatives during the economic lifetime of the plant (20 years). The aim of evaluating different sizes of heat pumps was to make an estimation of the economic sustainability of installing an HRU. For each case and at each data point the demand for each energy source, i.e. solar, Heat Recovery and biomass, was calculated. For all cases and at each design point the full energy potential from the solar roof was used as primary heating source. The energy delivered from the solar roof was calculated using the ambient temperature and relative humidity, the solar irradiation and a volumetric air flow of 180,000 $m^3$/h. The load delivered from the heat recovery system varied dependent on the ambient conditions, amount of heat recovered, i.e. from 0 to 4 MW, and on the amount of heat delivered by the solar roof. If the demand of the dryer was covered without using the full potential of the heat pump the model assumes that the remaining heat is emitted. To cover the peak load the boiler was designed to ensure that the entire demand was covered at each data point.

**3.2 Techno-economic assessment**

Total Lifetime Cost (TLC) of the different system designs were calculated as a summation of the Total Annual Cost (TAC).

$$TLC = \left(\sum_{y=1}^{N} TAC^y\right) \qquad (1)$$

Where y denotes a year from 1 to N, for the economic lifetime of the plant. N = 20 years in this assessment. The TAC was calculated as a summation of the hourly cost for each hour of operation during one year, Eq(2).

$$TAC = \left(\sum_{i=1}^{M} TC^i \times Index^i\right) \times AOT/8{,}760 \qquad (2)$$

Where i denotes a datapoint from 1 to M, where M is the total amount of datapoints, i.e. 79, and Index represents the size of datapoint i, i.e. the number of hours aggregated in the datapoint. AOT is the annual operating time of the plant, which is 8,060 hours in this assessment. Since the hourly cost has been estimated for 8,760 time points the AOT is divided by 8,760 to account for the availability of the plant on a yearly basis. This is done since the exact time points where the plant is down are unknown. The Total Cost at datapoint i, $TC^i$, was defined as in Eq(3). The size of the HRU and the boiler were set to cover the peak demand during the year.

$$TC^i = \left(I^i_{Scrb,max} + I^i_{HP,max} + I^i_{Boiler,max}\right) \times CRF/8{,}760 + EC^i_{HP} + FC^i_{Boiler} \qquad (3)$$

Where $EC_{HP}^{i}$ and $FC_{Boiler}^{i}$ denotes the electricity cost for the heat pump and the fuel cost for the boiler at datapoint i. 8,760 refers to the total number of hours per year in the calculation and the Capital Recovery Factor (CRF) for the system investments was estimated according to Eq(4). Total investment cost has been estimated per hour by dividing CRF with 8,760.

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{4}$$

Where r denotes the interest rate, 9 %, and n the economic lifetime, 20 y. The investment cost for the prefabricated boiler was calculated using the almost linear correlation bellow

$$I_{Boiler}\ (€) = 1{,}000 \times\ (125\ +\ 0.2357\ \times capacity) \times LF_{Boiler} \tag{5}$$

For calculating the investment cost of the heat pump Eq(6) was used, and Eq(7) was used for the scrubber. The Chemical Engineering Plant Cost Index (CEPCI) for 2007 (525.4) and 2018 (603.1) were used. The investment cost of the heat pump was calculated as a sum of capital cost for the condenser, evaporator and compressor. The investment costs for the condenser and evaporator were based on the largest heat exchanger area and the investment cost for the compressor was based on the data point with the largest electricity requirement. For the scrubber the investment cost was based on the volume flow of the wet exhaust gases.

$$I_{HP}(€) = \frac{CEPCI^{2018}}{532.9} \times \left(26{,}000 + 2{,}700 \times {P_{max}^{i}}^{0.75}\right) \times \frac{USD}{EUR} \times LF_{compr} + \frac{100}{0.09} \times \left( {A_{Cond,max}^{i}}^{0.778} + {A_{Evap,max}^{i}}^{0.778}\right) \times \frac{USD}{EUR} \times LF_{HX} \tag{6}$$

$$I_{Scrb}(€) = 37{,}000\ \times \frac{CEPCI^{2018}}{CEPCI^{2007}} \times \left(\frac{Q_{max}^{i}}{Q_{ref}}\right)^{0.7} \times \frac{USD}{EUR} \times LF_{Scrb} \tag{7}$$

Where $Q_{ref}$ = 36,000 $m^3$/h, USD/EUR = 8/10, $P_{max}^{i}$ installed electricity power in kW and $A^i$ in $m^2$. The Lang factor of the boiler ($LF_{Boiler}$) is set to 2, the Lang factor of the compressor ($LF_{Compressor}$) is set to 2.5, the Lang factor of the scrubber ($LF_{Scrubber}$) is set to 3.5 and the Lang factor of the heat exchanger ($LF_{HX}$) is set to 3.5.

## 4. Result

The results for variating the size of the heat pump for different energy markets scenarios are shown in Figure 3.

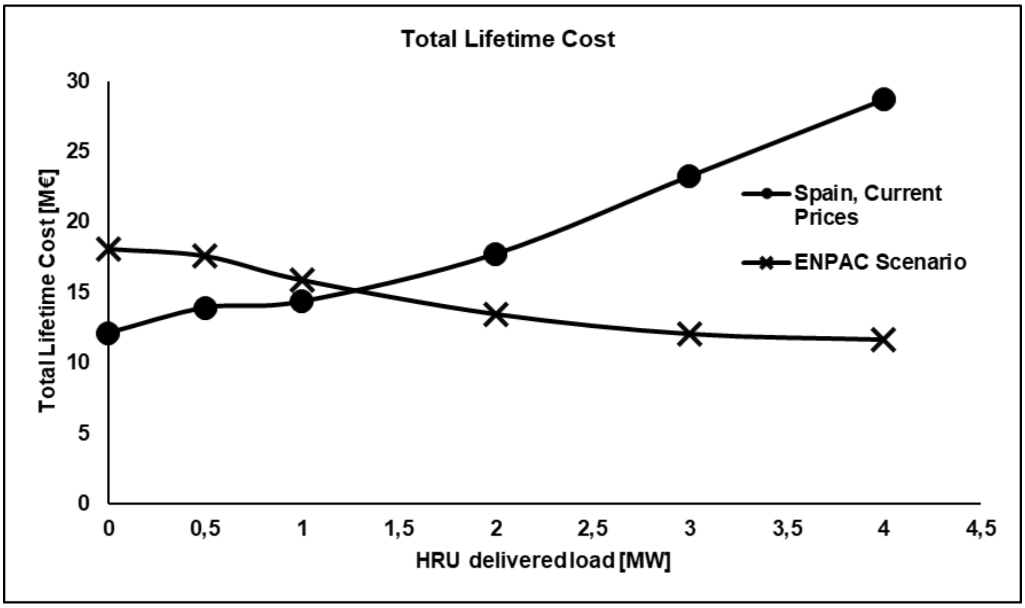


*Figure 3: Comparison in TLC for ENPAC Scenario and Spain current prices for different HRU, 0, 0.5 1, 2, 3 and 4 MW. The solar roof is excluded from the TLC.*

Figure 3 shows that the TLC of the system without heat recovery is higher for the ENPAC scenario than the Spain current prices, and that the TLC decreases for the ENPAC scenario and increases for Spanish scenario with increased heat recovery capacity. For ENPAC the figure also indicates that the decrease in TLC after 3 MW flattens out. The reason that the trend flattens after 3 MW depends on two things. The first reason is that the model is based on the assumption that the air flow into the scrubber is fixed, which gives that the COP decreases for larger systems since the temperature lift needs to be higher as more heat is extracted from the scrubber. The second reason can be understood by comparing the temperature out of the solar roof for the 79 aggregated data sets and the corresponding heat demand for each of these sets. For some sets a small load is required to meet the demand, decreasing the time the heat pump can operate at full potential, in this case from 100 % to 45 % between 0 and 4 MW installed capacity. These factors the result is also dependent on the climate data and the relationship between fuel cost and electricity cost (i.e. $C_{Fuel}/C_{Electricity}$). For an HRU to be relevant in the simulated system the $C_{Fuel}/C_{Electricity}$ needs to be below 5. The estimated prices for electricity and biomass in Spain, 9 €/MWh for biomass and 140 €/MWh for electricity, indicate that implementation of a heat recovery system is not economically viable. Comparing the electricity prices used in this study with the electricity price in 2019 for European counties from Eurostat it can be seen that there is a large variation and uncertainty related to the estimation, and a more thorough assessment would be needed in order to draw more specific conclusions on making investments in heat recovery (Eurostat Statistics Explained, 2019).

## 5. Conclusions

This paper has analysed the integration of a Heat Recovery Unit into a system comprising of both solar and biomass-based preheating of air to a low temperature drying plant A model has been developed and used in order to assess the economic potential of the HRU for a plant based in Madrid, Spain. The results indicate that for Spanish conditions the HRU is not likely to be feasible compared to a biomass-based hot water boiler. The study reveals that for integration of the Heat Recovery Unit to be interesting from an economic perspective a low electricity cost is needed in relation to the biomass cost. The relationship between fuel cost and electricity cost (i.e. $C_{Fuel}/C_{Electricity}$) needs to be below 5 in the specific study conducted. This ratio will depend on the location of the drying system due to the variations in meteorological conditions. The designed model can be applied to other locations in order to study the potential benefits of heat recovery, but then the input data needs to be changed (i.e. meterological information and economic inputs like electricity and biomass prices). Future work to improve the accuracy of the model and assessment includes addition of detailed knowledge of the dryer performance and an optimization of the operational strategy for the entire system throughout the year.

### Acknowledgements

This research has been supported by the EU project “Fast Track to Innovation - FTI”, DRALOD is co-funded by the European Commission - Horizon 2020 Programme - under Grant Agreement 820554. The DRALOD project is a collaboration between PERNIA, DBFZ, ÖKOTHERM and RISE. For more information about DRALOD please visit dralod.com.

## References

Alves-Filho O., 2018, Energy effective and green drying technologies with industrial applications. Chemical Engineering Transactions, 70, 145–150.

Axelsson E., Bisaillon M., Löfblad, E., 2018, ENPAC 2.1 – update of the wood fuel module, Profu.

Bell I.H., Wronski J., Quoilin S., Lemort V., 2014, Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library coolprop. Industrial & Engineering Chemistry Research, 53(6), 2498–2508.

Eurostat Statistics Explained, 2019, Electricity price statistics <ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics> accessed 29.04.2020.

Grubbauer A., Fluch J., Brunner C., Ramschak T., Wilk V., Fleckl T., 2018, Renewable and highly efficient energy systems through innovative combination of solar thermal and heat pump systems. Chemical Engineering Transactions, 70, 745–750.

IEA, World Energy Outlook, 2018, International Energy Agency <iea.org/reports/world-energy-outlook-2018> accessed 29.04.2020.

Marechal F., Muller D., 2008, Energy management methods for the food industry, Handbook of Water and Energy Management in Food Processing. Woodhead Publishing/Elsevier, 221–255.

Meteotest, 2018, Meteonorm. <meteonorm.com/en/> accessed 29.03.2020.

Schosser F., Arpagaus C., Wamsley T. G., 2019, Heat pump integration by Pinch Analysis for industrial applications: a review. Chemical Engineering Transactions, 76, 7–12.