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Renewable and Highly Efficient Energy Systems Through Innovative Combination of Solar Thermal and Heat Pump Systems

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Solar thermal heat and heat pumps are key technologies to increase the share of renewable energy in industry and to facilitate an independent energy supply. Within the Austrian research project “Renewable process heat – integration of solar thermal energy and heat pumps in industrial processes” (short EnPro) 12 industrial case studies were performed and have shown the high potential for combined solar heat and heat pump systems in industry on supply as well process level integration. Based on the assessment of different combination concepts from a technical and economic point of view, standardised integration concepts for the combination of the two renewable technologies were developed. Thereby, a high multiplication potential can be realised for industrial applications. For a maximum impact, an easy-to-use tool was developed to identify and evaluate the potential for increasing energy efficiency and the integration of solar thermal heat and/or heat pump systems in industry.

1. Introduction

In 2016 the industry consumed 25 % of the final European energy demand. (Eurostat, 2018) Industrial process heat accounts for 74 % of the industrial energy demand worldwide and half of it is low to medium-high temperature. (Philibert, 2017) Therefore industry presents a promising application area for renewable technologies such as solar thermal heat and heat pumps to produce process heat and substitute fossil supply systems. According to Weiss et al. (2017) more than 500 solar thermal plants with an overall installed collector area of 416,414 m² for providing solar heat for industrial process are installed worldwide. The integration of heat pumps for providing industrial process heat is investigated in several studies like Walmsley et al. (2017) where the integration of heat pumps in dryers are examined. For the combination of solar thermal heat and heat pump research activities can be found in the building sector. System variants and improvements are analysed in Poppi et al. (2016). Combined systems for supplying domestic hot water and space heating are already available on the market. For the combined integration of the two renewable energy systems in industrial applications no current research activities can be found in literature. Schmitt (2015) shows a classification for the integration of solar heat in industrial processes and heat supply systems. Approaches for simplified integration of combined renewable energy technologies are not available.
In 2015 the Austrian research project “EnPro” was launched by a consortium of AEE INTEC, AIT Austrian Institute of Technology and Technische Universität Wien. The overall objective of the project was to develop an appropriate planning guideline combined with an evaluation tool with special focus on efficient and cost-effective integration concepts for solar heat and/or heat pump systems in industry. In this work the methodology for evaluating the potential in industry for solar thermal heat and/or heat pumps, the function of the evaluation tool as well as the developed combined integration concepts will be discussed.

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2. Method

2.1 Case studies

A total of 12 case studies were carried out to evaluate the potential for the industrial process heat supply by renewable energy systems like solar thermal heat, heat pump systems or combined energy systems. The case studies belonged to the following five industrial sectors: (1) food and beverage, (2) metal production and processing, (3) pulp and paper, (4) production of insulation and (5) laundries. The choice of sectors ensured high potential for application of solar heat and heat pumps and guarantees a high degree of replicability in different industrial sectors and applications.

As a first step, the current situation of energy supply and consumption of the 12 companies was analysed according to the European standard for energy audits in industry EN 16247. General company data (e.g. production volume, energy sources and consumption) and specific parameters of processes and energy supply (e.g. temperature, operating time, daily and seasonal demand) were obtained to evaluate the status quo of the companies. Afterwards process optimisation measures such as increasing process efficiency via reduction of energy and material losses and integration of best available technologies were evaluated, followed by system optimisation (heat and cold supply optimisation, heat recovery). The Pinch analysis was used as methodology to identify the theoretic heat recovery potentials (see Kemp, 2007). Based on this, technical and economic feasible heat recovery networks were designed to achieve optimised energy recovery. For the remaining heat demand, the potential to implement renewable energies like single or combined solar thermal and/or heat pump systems were evaluated. Therefore, key criteria were defined, that indicate whether a company is suitable to establish solar thermal heat, a heat pump or a combined system. In addition to that, a decision tree was developed. Those criteria include local circumstances (available roof or ground area, inclination angle of roof to south/southeast/southwest, roof static, space for installing a storage), process heat temperature (solar thermal <90 °C; heat pump <125 °C), possible heat sources (in terms of temperature and distance) for heat pump (e.g. processes with cooling demand, waste heat from cooling machines, compressors, waste water or exhaust air from the process to be supplied or other processes).

In total, the status quo evaluation has shown that about 2.1 TWh of energy were consumed in the 12 companies per annum. The most energy consuming companies per site were found in the pulp and paper industry. Natural gas was the energy source most common used with 78 % of total energy consumed in all companies, followed by electricity with 12 %. The remaining energy demand was covered by fuel oil, coal and other energy sources. In total, feasible process and system optimisation measures with the potential to reduce the energy consumption by over 3.3 TWh/y were identified, resulting in a reduction of CO_2-equivalent of approximately 818 t/y. In the food and beverage industry the integration of heat exchangers for heat recovery from shock freezers, steam and chillers were the most popular optimisation measures. In metal production and processing, measures such as the covering of electroplating baths and heat recovery from air compressor were identified. In laundries, optimisations can be achieved by air preheating of finisher, dryers and steam boiler as well as the use of calendar waste heat for preheating of water and dryer air.

For the implementation of renewable energy systems various possible integration points were assessed in the single case studies. Integration concepts on process as well as system level were developed based on the requirements of the processes or the supply system. The performance of single and combined supply systems (parallel and serial) was evaluated based on technical and economic criteria (optimised temperature levels, supply efficiencies, etc.). Depending on the key criteria defined, some technologies or combinations were already excluded from the beginning (e.g. roof shading by a hill). The potential single or combined renewable technologies were analysed in detail and compared from a technical and economic point of view (static and dynamic calculation including levelised cost of heat). By the integration of the concepts a total reduction of CO_2-equivalent of 19,000 t/y could be achieved.

2.2 Integration concepts

Solar thermal and heat pumps can be integrated monovalent or as combined system to supply a process with heat. To offer planners, control engineers, technology providers and industrial companies different efficient and economic integration concepts that could be applied in different and broad industrial applications, generalised concepts for the combined integration were developed. Based on the case studies a parallel and three different serial combination concepts were identified and evaluated positively with a high potential from technical and economic point of view. In all concepts waste heat from processes or solar thermal heat is used as source for the heat pumps. Ambient air or ground water is neglected.

In the parallel combination the two technologies provide process heat independently from each other as shown in Figure 1. The heat pump uses industrial waste heat streams as heat source. If the heat source is a cooling process, the efficiency of the overall integration system is increased by heating and cooling at the same time. For optimal use of the parallel integration concept, both renewable technologies must reach independently the required temperature level of the process. The conventional supply system would then be obsolete. The results of the case studies have shown that the combination is particularly efficient if:

- there is potential for solar thermal and heat pump (local circumstances, temperature, heat sources etc.),
- one technology alone is not sufficiency to cover the process heat demand to the desired extend,
- there is not enough space for a complete coverage with solar thermal system,
- the heat source is insufficient for complete coverage with the heat pump.

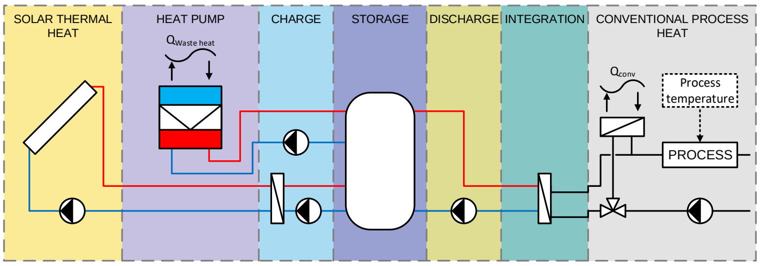

Figure 1: Parallel integration concept for solar thermal heat and heat pump from Wilk et al., 2017

Three serial concepts were developed. In the concept seen in Figure 2 the heat transfer medium is first preheated with the solar thermal collector, followed by the heat pump. For this purpose, a heat source for the heat pump must be available at relatively high temperature (>50 °C). If the heat supply temperature of the heat pump is sufficient for the application, no further conventional heating is necessary. This combination can reach a high system efficiency if:

- heat is required at temperature level with low supply efficiency of a solar thermal system (>90 °C),
- high temperature heat source is available (>50 °C) leading to maximum supply efficiency of a heat pump.

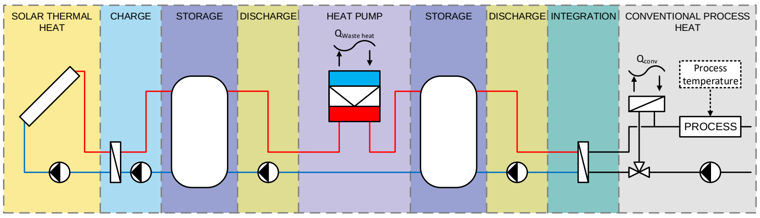

Figure 2: Serial integration concept I for solar thermal heat and heat pump from Wilk et al., 2017

In the second serial concept the solar thermal system is used after the heat pump as seen in Figure 3. In this case, a first increase of temperature of the heat transfer medium is realised by the heat pump and then the solar collector does the preheating. For an efficient and economical operation of the system, it is recommended to use a cooling process as heat source for the heat pump. The combination is particularly well suited for industrial applications where:

- only “cold” heat sources are available for the heat pump (< 30 °C),
- the temperature of the heat pump is reduced to an economical level (maximised COP).

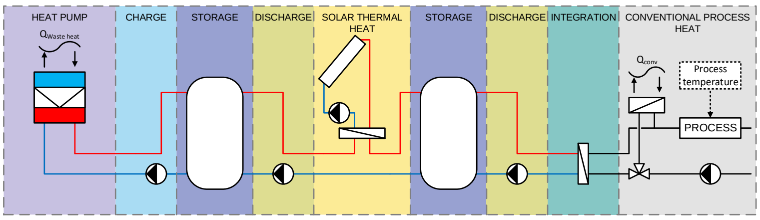

Figure 3: Serial integration concept II for solar thermal heat and heat pump from Wilk et al., 2017

If no process heat sources for the heat pump are available in the company (and ambient heat is not sufficient for the economic operation of a heat pump), the solar thermal system can serve as heat source for the heat pump. Proper storage dimensioning ensures that the heat pump can operate continuously. The combination, shown in Figure 4, is particularly well suited for industrial companies if:

- no heat source is available,
- the temperature level of the environment is too low for the economic integration of a heat pump.

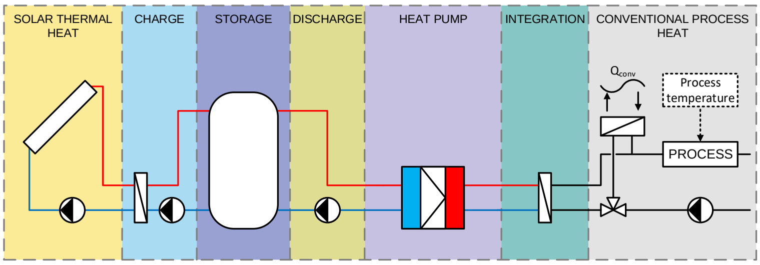

Figure 4: Serial integration concept III for solar thermal heat and heat pump from Wilk et al., 2017

The findings of the case studies and the identified concepts and conclusions were used as a basis for an evaluation tool respectively a decision matrix. With these the potential user can evaluate which of these integration concepts is the most appropriate (technical and economical) for supplying a certain industrial process with renewable process heat.

2.3 Evaluation tool

Currently available tools are either detailed planning tools for the implementation of renewable energies like solar thermal heat and heat pumps, usually require previous knowledge in simulation or programming, are addressing only one technology or are not combining energy efficiency measures with renewable energy integration. Thus, the evaluation tool developed within “EnPro” supports the user to identify the potential for energy efficiency measures and integrating the most suitable concept of solar thermal heat and/or heat pump systems in industry simply and user-friendly. Hence, this tool is based on high level background calculations, the identified concepts are a good basis for the industry to decide on potential next steps.

The tool was developed in MS Excel 2010 using VBA programming for some parts of the calculations (e.g. the PINCH algorithm and heat exchanger design) and for providing intuitive and easy user handling. The technical requirement for using the tool is the installation of MS Excel 2010 or better. The tool can be downloaded from the website of the project partners and the Austrian funding agency. The target group of the evaluation tool are consultants, technology suppliers, control engineers and energy managers (or other responsible persons from industry itself). The tool was especially developed for the industry sectors analysed within “EnPro” (food and beverage, metal production and processing, pulp and paper, production of insulation and laundries), however as similar industrial processes can be found in other processing industry sectors too, a “free” branch with no specific processes and process optimisation measures was added.

The user starts by entering basic data of the company like location, ambient conditions (fresh water temperature, ambient temperature) and available space (ground and roof) for installing solar thermal heat. Afterwards the status quo of the energy flows within the company is defined by the user. Therefore, the yearly amount of energy resources needed (e.g. natural gas, biomass, fuel oil, bought-in steam, etc.) and their energy value must be specified followed by choosing energy conversion technologies (hot water boiler, steam boiler, chiller and air compressors) used in the company to transform parts of the purchased energy sources into useful energy carriers such as hot water, cooling water or steam. The boilers are defined by the user entering the nominal power, the yearly full load hours and the boiler efficiency. Latter can be assumed by the user or calculated by the tool based on entering O_2-value and flue gas temperature. Chillers and air compressors are calculated similarly. For chillers the main indicator is the Energy Efficiency Ratio (EER) which can be assumed by the user or calculated by entering evaporating and condensation temperature. After defining the energy supply, the distribution losses for the useful energy carriers can be entered by the user.

Once general, energy supply and distribution data are entered, different kinds of processes can be defined in a simple way. Pre-defined process steps can be chosen. For example, in the metal production and processing industry the energy consumption of galvanizing baths is calculated by the sum of energy needed for heating up (calculated by entering mass flow, specific heat capacity and temperature difference) and for temperature compensation (calculated by entering the energy losses of the bath). For specific processes the waste heat streams like waste water streams or humid air are calculated by the tool by entering process specific data (mass flow, specific heat capacity and temperature). In case of humid air, the specific heat capacity of the stream is calculated by the tool depending on the kind of energy used (sensible or latent) and the cooling

temperature specified by the user. Especially for the use as heat source for the heat pump the possibility to define and calculate the energy content of humid air is essential.
After definition of supply, distribution and processes the energy balance can be checked by the user and is visualised with diagrams. By this the user has the option to check if the energy balance is inconsistent and if necessary a verification of parameters like the efficiency of utilities, part load factors, running hours etc. can be done to close the energy balance (see Figure 5).

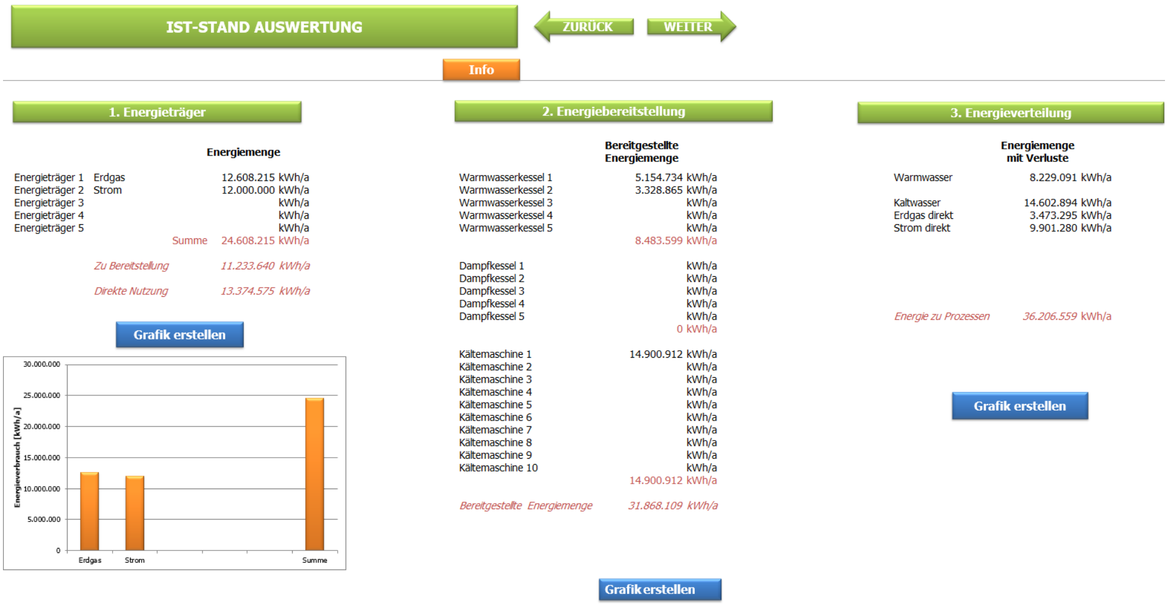

Figure 5: Energy balance in the evaluation tool

Based on the definition of the status quo and the selected industry branch, process and system optimisation measures are suggested. The process optimisation is not calculated in the tool however, the user obtains vast and detailed branch specific information and options for optimisation (e.g. best available technologies) by a link to the EnPro WikiWeb (developed based on the AEE INTEC WikiWeb called “Efficiency Finder”). To obtain options for system optimisation measures, a Pinch analysis is performed automatically retrieving all data from process and waste heat streams that were defined in the status quo section of the tool. An algorithm suggests feasible heat exchangers by combining streams with heating demand (cold streams) and streams with cooling demand (hot streams). By entering the costs of a heat exchanger, the feasibility is calculated. Automatically all feasible heat exchangers are ranked in the tool depending on size, transferred energy and exergy loss offering the user an easy option to choose the most suitable heat exchanger(s) for the company. Hot streams with too low temperatures to use in a heat exchanger could be used as heat source for the heat pump.
Finally, the integration of solar thermal heat and/or heat pumps is technically, economically and ecologically evaluated. The user can assess the single integration of solar thermal heat and heat pumps or the 4 combined integration concepts of the two systems described in the chapter above. For each integration option at the beginning the process or the processes to be supplied by renewable process heat must be selected. In case of the heat pump a heat source must be selected too. For the integration of solar thermal heat, the user can choose between ground or roof installation and choose between different types of flat plate collectors which vary in price and efficiency. Afterwards the size of the collector area is suggested by the tool and can be altered by the user in case the plant size is to big resulting in a reduction of the annual solar yield and the annual solar coverage. The heat pump is designed depending on the temperatures of the heat source and sink and the energy demand required. For the parallel integration the user must define the percentage distribution of the process heat demand that should be supplied by the heat pump and solar thermal heat. The tool evaluates whether this distribution could be achieved or not. E.g. for the “serial integration concept I”, the user must define the temperature that should be achieved by the solar thermal heat limited by a maximum temperature of 90 °C. For the “serial integration concept II”, the same must be defined for the heat pump. The maximum temperature for the heat pump are 125 °C. For the “serial integration concept III” the final temperature of the solar thermal heat must be defined. Finally, the integration concepts defined by the user

are compared based on a technical, economic and ecologic evaluation using key parameters as e.g. energy and CO_2 savings, efficiency, COP, payback period, energy production costs. By this the tool provides a good basis for the user to identify and evaluate the potential of the integration concept.

3. Conclusions

The results presented in this paper are summarised in a guideline for the target group consisting of planners, technology suppliers, control engineers and energy managers (or other responsible persons from industry itself). The energy audits identified high potential for energy efficiency measures and especially for the integration of the renewable energy systems solar thermal and heat pump in industry. The results show that by the integration of renewable energies in industrial applications the CO_2 emissions can be significantly reduced. For the integration of combined renewable energy systems there are various possibilities. Solar thermal and heat pumps can be integrated monovalent or as combined system depending on the framework conditions of the industrial company. To offer planners, control engineers, technology providers and industrial companies different efficient and economic integration concepts that could be applied in various industrial applications, generalised concepts for both, the single and the combined integration of solar thermal and heat pumps were developed. A parallel and three different serial combination concepts were identified to be the most promising, visualised in a modular structure which offers a high adaptability. The results of the case studies and the identified concepts were integrated in an evaluation tool which shows the user of the tool the potential for increasing energy efficiency and for the integration of solar thermal heat and/or heat pump systems in industry. In the future, further effort must be made to increase the share of renewables energies in industry to further minimise the CO_2 emissions and to set the framework conditions for a flexible and independent energy supply of the Austrian and European industry.

Acknowledgments

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