Energy xxx (2017) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Optimal energy supply structures for industrial food processing sites in different countries considering energy transitions

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ARTICLE INFO

Article history:
Received 23 December 2016
Received in revised form
13 April 2017
Accepted 7 May 2017
Available online xxx

Keywords:
Energy transition
Combined heat and power
Heat pump
Separate conversion
Greenhouse gas emissions
Primary energy factor

ABSTRACT

This study focuses on analysing the most energy efficient utility system supply structure in terms of carbon emissions, primary energy efficiency and energy costs. In the German food processing industry, the state-of-the-art technologies in the utility supply structure are a gas fired steam boiler for steam generation and ammonia chillers for chilled water generation. Low investment costs and its durability are attractive for industrial production sites. But, given the ongoing energy transition to renewable energy, opportunities to reduce emissions will become increasingly important. There are other energy supply options, such as Combined Heat and Power and Heat Pumps, that need to compete against the conventional energy supply systems. In the short-term, countries with presently high electricity Grid Emissions Factors (GEF) such as Germany and the USA, the use of decentralised CHP results in savings of primary energy and emissions. This option is less attractive for countries with already low GEF such as Norway. It is also less attractive in the long-term for countries like Germany as the on-going energy transition towards renewables is anticipated to decrease the current GEF by 50% in 2030. In these cases of low GEF, HP solutions provide the lowest emissions and highest primary energy efficiency.

1. Introduction

The goal of 195 nations is to reduce the risks and impacts of climate change agreed by contract, of Paris world climate conference 2015. The main objectives of the agreement are to reach peak greenhouse gas (GHG) emissions by mid-century and holding the increase in the global average temperature below 2 °C above pre-industrial levels to address climate change. To reach these targets, all sectors, and especially the industrial sector, need to contribute to reducing GHG emissions by implementing energy efficiency measures at all stages of the energy conversion chain from generation to final consumption. As a result, over the next few decades, there will likely be a global pivot from heavy reliance on fossil fuels to the wide-spread uptake of renewable energy opportunities.

Country scale evaluations of emissions reduction options are useful for setting overall targets and informing Government policy. For example, Gerhardt [1] report that heat pumps (HP) are a key technology to decarbonise the residential and commercial heat energy market in Germany, whereas combined heat and power (CHP) is advantageous for industrial processes that need high temperatures and steam. Omid et al. [2] are investigating heat pump integration from a technical perspective in a slaughterhouse in Canada, Miah et al. [3] for a confectionery factory in the UK and Kapustenko et al. [4] for a cheese production in Ukraine. Walmsley et al. [5] reports about the appropriate placement of an open cycle heat pump in vapour recompression for the milk industry. Janghorban et al. [6] analysed for vapour-compression refrigeration and Shahandeh et al. [7] for distillation columns in methanol-water separation in detail the optimisation of heat pump integration in industrial processes. Hedegaard et al. [8] investigated the use of domestic heat pumps to store wind energy as hot water, linking the

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http://dx.doi.org/10.1016/j.energy.2017.05.062

electricity and residential sectors. Meyers et al. [9] surveyed 249 companies of the food and beverage industry for lowering GHG emissions. They identified heat pumps and CHP as feasible solutions for emission reduction but focus only on today's status quo. Recent research papers focusing on the economic and ecologic impacts of broad-scale implementation of new technologies in Latvia [10], Saudi Arabia [11], UK [12], France [13] and Norway [14] are also reported. In other cases, studies have looked at assessing the energy and carbon emission savings by one or two technologies such as cogeneration [15], carbon capture and storage [16], or electrification [17] for an entire industrial sector. Other focus on national strategies for the whole power systems [18] for Portugal, UK, Brazil, China and the European Union [19] on ex-post data. However, such reports leave a gap between the overall national strategy and what are the realistic and economic solutions to implement at specific plants and sites. This paper attempts to connect high-level strategy with industry- and plant-level strategic action and implementation.

The food processing industry traditionally uses steam boilers and ammonia compression chilling machines for heat supply [20]. A common measure to decrease energy costs and increase energy efficiency is the application of gas engine CHP for heat supply [21]. Whereas heat pumps as an option for combined heat and cold are a currently discussed technically feasible option [4]. The aim of this paper is to investigate how the optimal energy supply structure for individual industrial sites, based on GHG emissions and primary energy consumption, varies between countries in 2015, 2020, and 2030. The optimal energy supply structure solution depends on a country's available natural resources, primary energy factors, and electricity grid emissions factors, which determine the efficiency and environmental cost for providing final usable energy. In this way, national energy and emissions datasets for the present and projected future are linked to industrial plant data, to model the entire energy supply chain, from raw material through to refined energy, together with its associated emissions. Each industrial sector and each individual site have its own characteristic energy demand profile for process heat, chilled water, cooling water, and other utilities. The role of the energy supply structure is to convert natural resources, such as natural gas, to satisfy the required utility demands, e.g. steam. The impacts of the supply structure on cost and the environment are highly dependent on the energy source and the utilities used (i.e. Combined Heat and Power - CHP, Heat Pump - HP, Steam boiler).

This study reports the development of an EXCEL™ spreadsheet tool for analysing individual industrial sites to determine the optimal energy supply structure in terms of primary energy use, GHG emissions, and/or energy costs. The analysis tool is applied to two case studies. One of a representative cheese factory model that has been validated against industrial data. Another one of a typical medium-sized meat processing plant with energy measurement data from an online energy monitoring system. The scope of the analysis includes looking at how the optimal energy supply structure changes for cheese factories located in Norway, France, and the USA. Ongoing efforts of these countries are taken into account by estimating current and future Emissions Factors (EF) and Primary Energy Factors (PEF) comparing the supply structure in Germany in the years 2015, 2020 and 2030.

2. Rating of energy systems

The selection of an energy source has an important impact on the ecological emissions and the primary energy efficiency of a site. The upstream chain that is defined by the supplier or his products leads to significant efficiency losses and emissions. Typical values of losses from the energy source to final energy are in the range of 10–70%. Through the right choice, a company can directly influence the outcomes.

The first criterion is the extent of GHG emissions, which is summarised by a carbon dioxide equivalent (CO_2e). This criterion gives information about the environmental impact with specific reference to climate change.

The second criterion for comparison is the PEF, which is the ratio of the primary to the final energy. The advantageous of this measure is that it is a simple comparison and numerous data are readily available. The weakness of PEF is that it compares energy quantity at the same reference point, which is the Primary Energy, but does not consider energy costs, quality (e.g. exergy), and intensity, which characteristics of the energy source, i.e. the properties and potentials of natural gas, coal, uranium, hydro, wind energy, and solar differ.

3. An elementary understanding of energy systems in the dairy industry

Fig. 1 shows the conversion routes from primary to useable energy and the extent to which suppliers and processing companies can influence it. Large industrial sites are usually supplied by the medium voltage power grid (e.g. 10–30 kV). The voltage gets reduced in a transformer station and distributed to the site grid. The main electricity consumers are electrical drives, approximately 80%. These can move solid bodies, pump liquids or compress gases. Further important applications are electronics and illumination [22]. Supplying heat by electrical energy is uncommon, but a possible option. Resistance heating for high temperature heating (e.g. electric steam generator) with low investment costs and low efficiency or heat pumps with high investment costs and high efficiency for low temperature heating are implementation options.

Resource supply structures for national electricity grids and the associated Grid Emissions Factors (GEF) differ for each country due to differences in geography, resources, and political drivers. Although the various regions of one country have stark differences in the supply system, a country is usually the most logical overall system boundary. Fig. 2 shows the international comparison of PEF of electricity for the years 2015, 2020, and 2030 based on data from GEMIS (www.iinas.org). The corresponding GEFs are presented in Fig. 3. The lowest emissions have power systems based on renewable or nuclear power. Austria, Swiss, France, Sweden and Norway are the countries with the lowest emissions as shown in Fig. 3. Germany sits above the EU-27 average because of a high amount of coal power plants and the winding down of nuclear power. By 2030 Germany aims to reduce the 2015 GEF by 50% through good progress in the energy transition towards renewable energies.

Natural Gas remains an important energy source for supplying processes. It is used to supply steam, hot water, and hot air for production processes as well as a process feedstock. Utilities using fossil fuels produce heat with high temperatures and exergy. These are therefore too valuable to only use it for low temperature heating. CHP improves the exergy efficiency of using fossil fuels, particularly for low temperature heating applications. Natural gas is very good fuel in terms of emissions factor and primary energy efficiency as visualised as a dotted line in Figs. 2 and 3.

In this paper, three conversion technologies on a company level are analysed. The separate conversion (SP) with boiler and compression chiller is the present industry standard. It comes along with unavoidable losses of thermal energy. In boilers, heat at a high temperature level is generated (above 1000 °C [23]) but only required in dairy processing for heating fluids to 50–140 °C, which leads to significant exergy destruction. Another significant loss is waste heat in the boiler exhaust. The exhaust temperatures are often >120 °C, which is well above the typical Pinch Temperatures

Please cite this article in press as: Philipp M, et al., Optimal energy supply structures for industrial food processing sites in different countries considering energy transitions, Energy (2017), http://dx.doi.org/10.1016/j.energy.2017.05.062