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Optimal Energy Supply Structures for Industrial Sites in Different Countries Considering Energy Transitions: A Cheese Factory Case Study

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This present study focuses on analysing the most efficient utility energy supply structure in terms of primary energy efficiency, carbon emissions and energy costs. In the German dairy industry, separate conversion with gas fired steam boiler, and cooling with ammonia chillers are the-state-of-the-art technologies. It is attractive due to its robustness and low investment costs. 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 (CHP) and Heat Pumps (HP), that if implemented need to compete against the conventional energy supply systems. One option is CHP to provide cogenerated electricity and heat while cooling remains supplied by ammonia chillers. In countries with 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. However, this option is less attractive for countries with low GEF such as France and Norway, and for places like Germany where the energy transition lowering its GEF by 50 % in 2030. In these cases, HP solutions provide the lowest emissions and highest primary energy efficiency.

1. Introduction

Reducing the risks and impacts of climate change is the goal of 195 nations, which signed the Paris Agreement. Reaching peak greenhouse gas (GHG) emissions by midcentury and holding the increase in the global average temperature well below 2 °C above pre-industrial levels are the main objectives of the agreement to address climate change. In order to reach these targets, all sectors, and especially the industrial sector, need to contribute to reduce GHG emissions by implementing energy efficiency measures at all stages of the energy chain from generation to final consumption. As a result over the next few decades there will be a global pivot from heavy reliance on fossil fuels to 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 et al. (2015) report that HPs are a key technology to decarbonise the residential and commercial heat energy market in Germany, whereas CHP is advantageous for industrial processes that need high temperatures and steam. Recent research papers focusing on the economic and ecologic impacts of broad-scale implementation of new technologies in Latvia (Blumberge et al., 2014), Saudi Arabia (Nizami et al., 2015), and Norway (Becidan et al., 2015) 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 (Fuentes-Cortés et al., 2015) and carbon emissions capture and storage (Ishak et al., 2015) for an entire industrial sector. However, these types of analysis still leave a gap between national strategy and realistically implementing these ideas at individual plants and sites.
The design of most efficient energy supply structure for individual sites in terms of primary energy consumption and GHG emissions varies for each country depending on the different available natural resources, primary energy factors and emissions factors for providing final useable energy forms. Each

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industry sector and individual site has its characteristic energy demand profile of steam, process heat, chilled water, cooling water, and other utilities, which the energy supply structure needs to meet by converting natural resources into such utilities. 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 a case study of a representative cheese factory model that has been validated against industrial data. 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 Primary Energy Factors (PEF) and Emissions Factors (EF) and comparing the supply structure in Germany in the years 2015, 2020 and 2030.

2. Rating of Energy Systems

The selection for an energy source has an important impact for the primary energy efficiency and the ecological emissions of a site. The upstream chain that is defined by the supplier or his products leads to significant efficiency losses and emissions. Through the right choice a company can directly influence the outcomes.
The first criteria for comparison is the PEF, which is the ratio of the primary to the final energy. The advantageous of this measure is that a simple comparison and data is readily available. The weakness of PEF is that it is only comparing energy quantity at the same reference point, which is the Primary Energy, but does not take into account energy costs, quality (i.e. exergy), and intensity as determined by the characteristics of its source. For example, there are large differences in the properties of natural gas, coal, sun, wind, and uranium.
The second criteria is the quantity of GHG emissions, which is summarised by a carbon dioxide equivalent (CO_2e). This criteria gives information about the environmental impact with specific reference to climate change.

3. An Elementary Understanding of Energy Systems in the Dairy Industry

Figure 1 shows the conversion path from primary to useable energy and the area of influence of processing companies and suppliers. 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 majority, approximately 80 %, is typically used for electrical drives. These can move solid bodies, pump liquids or compress gases. Further important applications are electronics and illumination (Pent et al., 2001). The usage for process heat supply is rare today but a possible option. Resistance heating for high temperature heating (e.g. electric steam generator) or heat pumps for low temperature heating are implementation options.

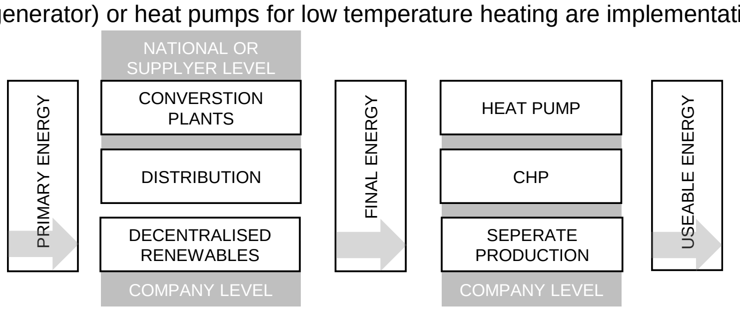

Figure 1: Conversion pathway of natural resources (Primary Energy) into Useable Energy

Resource supply structures for national electrical grids and the associated Grid Emissions Factors (GEF) differ for each country due to differences in geography, resources, and political drivers. Even though in countries, like Germany, the various regions have stark differences in the supply system, a country is usually the most logical overall system boundary. Figure 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 Figure 3. The figures show that renewable or nuclear power based energy systems like those of Austria, Swiss, France, Sweden and Norway have the lowest emissions. 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 visualized as a dotted line in Figures 2 and 3.

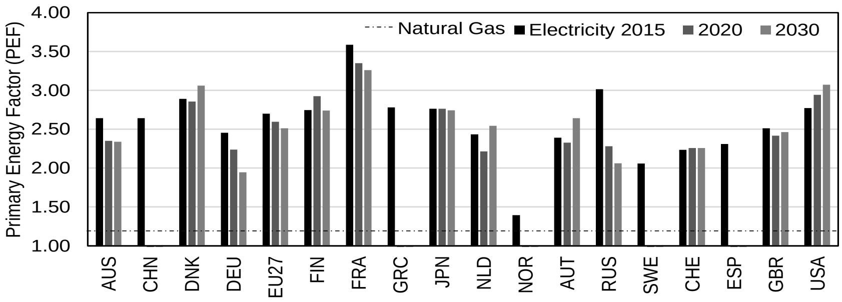

Figure 2: Primary Energy Factors for various countries in 2015, 2020, and 2030 (Data from GEMIS)

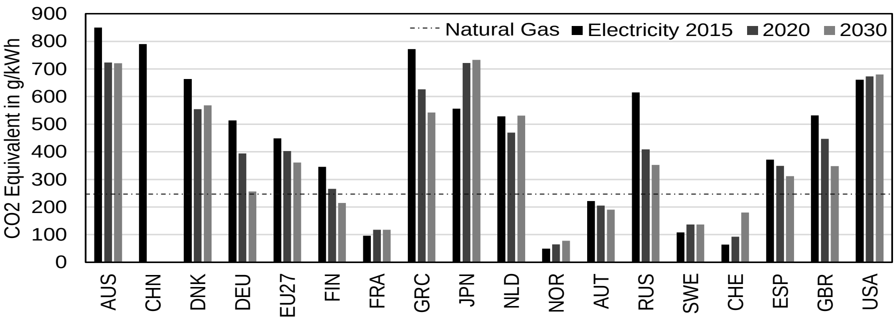

Figure 3: Grid Emissions Factors for various countries in 2015, 2020, and 2030 (Data from GEMIS)

4. Methods

The GEMIS database provides primary energy and emission factors for natural gas and electricity. The values for natural gas are constant for all countries and future scenarios. Whereas factors for electricity are highly dependent on the individual country due to significant differences in the share of renewables, nuclear power, gas and oil powered plants. Moreover, many nations are in the progress of increasing the share of renewables and energy efficiency, which impacts the framework conditions for industrial energy supply structures. For the future scenarios, data estimates are extracted from GEMIS. For EU countries, the scenarios are based on the European Policies to Promote Sustainable Consumption Patterns (EUPOPP), whereas Germany's future energy supply structure is predicted by Nitsch et al. (2014), who refers to the pilot study of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU). The primary energy and the CO_2-emissions are calculated by multiplying the country specific factors with the accumulated final energy demand of each utility. To determine the final energy on the plant level performance equations for a variety of utility supply systems for individual sites, together with their assumptions, are presented in Table 1. In addition, the calculations are stationary and the utilities work with a constant efficiency and their output fit the demand in the most efficient way. The analysis focuses on the comparison of the CO_2 emissions and primary energy of the different supply structures in the years 2015, 2020 and 2030.

5. Cheese factory case study

The evaluation of the tool is done by a case study on a cheese factory that processes 1 ML/day of raw milk. In the case study three different technologies are compared: Separate production (SP) of heat and power (grid), CHP with natural gas engine and heat pump cycles (HP) using grid electricity. A detailed process Pinch Analysis (Invented by Linnhoff 1979) has been carried out to provide the necessary utility demand data in Table 2.

Table 1: Utility supply options using natural gas and electricity

Utility	Equation	Condition	Assumptions
Steam Boiler	$E_{natural\ gas} = \frac{E_{hot\ water} + E_{steam}}{\eta_{steam\ boiler}}$	None	• Peak load boiler • Steam to hot water
Compression Chiller	$E_{electricity} = \frac{E_{cold}}{COP_{chiller}}$	None	
Heat Pump	$E_{electricity} = \frac{2 \cdot E_{cold}}{COP_{hp\ heat} + COP_{hp\ cold} - 1}$	$E_{cold} > 0$	• Demand of cold energy determines heat pump power •Heat surplus to cooling tower
	$E_{electricity} = \frac{E_{hot\ water}}{COP_{hp\ heat}}$	$E_{cold} = 0$	
Combined Heat and Power	$E_{natural\ gas} = \frac{E_{hot\ water}}{\eta_{CHP\ thermal}}$ $E_{electricity} = -E_{hot\ water} \cdot \frac{W_{el,CHP}}{Q_{th,CHP}}$	$E_{steam} = 0$	• Heat demand controlled electricity production • Max. steam – hot water ratio 43 % (3/7) • Surplus steam to hot water
	$E_{natural\ gas} = \frac{E_{hot\ water} + E_{steam}}{\eta_{CHP\ thermal}}$ $E_{electricity} = -(E_{hot\ water} + E_{steam}) \cdot \frac{W_{el,CHP}}{Q_{th,CHP}}$	$E_{steam} < E_{hot\ water} \cdot \frac{3}{7}$	
	$E_{natural\ gas} = \frac{E_{hot\ water} + E_{hot\ water} \cdot \frac{3}{7}}{\eta_{CHP\ thermal}}$ $E_{electricity} = -(E_{hot\ water} + E_{hot\ water} \cdot \frac{3}{7}) \cdot \frac{W_{el,CHP}}{Q_{th,CHP}}$	$E_{steam} \geq E_{hot\ water} \cdot \frac{3}{7}$	

Table 2: Input parameters for the model

Loads of Factory	Value	Unit	Efficiency of Utilities	Value
Hot water	15,000	MWh/y	CHP Efficiency thermal	0.45
Steam	600	MWh/y	CHP Efficiency electricity	0.41
Electricity	13,000	MWh/y	CHP coefficient	0.91
Ice water	22,000	MWh/y	Efficiency of thermal reference	0.9
Total	50,600	MWh/y	COP Compression chilling machine	4.5
			COP heat pump heating	2.6
			COP heat pump cooling	2.0
			Furnace efficiency factor	0.9

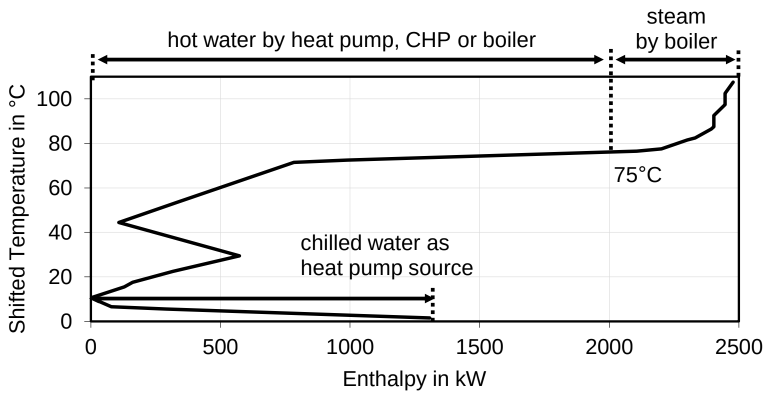

Figure 5: GCC of a cheese factory with integration points of utilities

The thermal energy is supplied on three levels. The Grand Composite Curve (GCC) is a method to show net heat flow added at the top of the cascade and removed at the bottom to tell the demand of hot and cold utilities (Kemp 2007). In Figure 5 it is shown for a cheese factory with the integration points of the utilities. The lowest level is chilled water at 1 °C, the first heating level of hot water is at 75 °C and a second heating level of steam at 4 bar (144 °C). The COPs for a compression chiller and a two stage ammonia heat pump are calculated by a MATLAB® Model using the CoolProp library from Bell et al. (2014). CHP and furnace efficiencies are taken from Schaumann (2010) and Effenberger (2000).
The price for electricity for the analysed dairy plant in Germany is 80 €/MWh and for natural gas 38 €/MWh (Department of Energy & Climate Change, 2015) with an assumed annual price increase for electricity of 3 % and for gas of 5 %.

6. Results and Discussion

The development of optimal energy supply structures for the cheese factory case study looked at the impact of its physical location (Germany, Norway, France, and the USA) and how the ongoing energy transition (2015, 2020, and 2030) affects the optimisation. Figure 6 shows the comparison of locating a cheese factory in Norway, a country with a large share of renewable energies, France with majority of nuclear power, the USA with a fossil fuel based system.

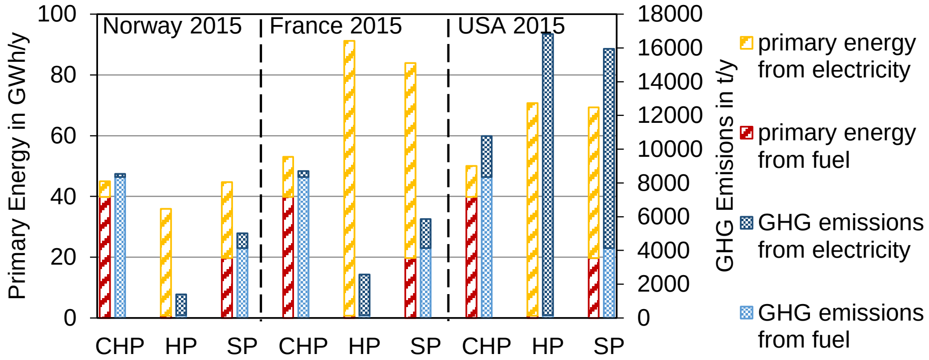

Figure 6: Comparison locating a cheese factory of Norway, France, and the USA on the performance of various energy supply structures in 2015

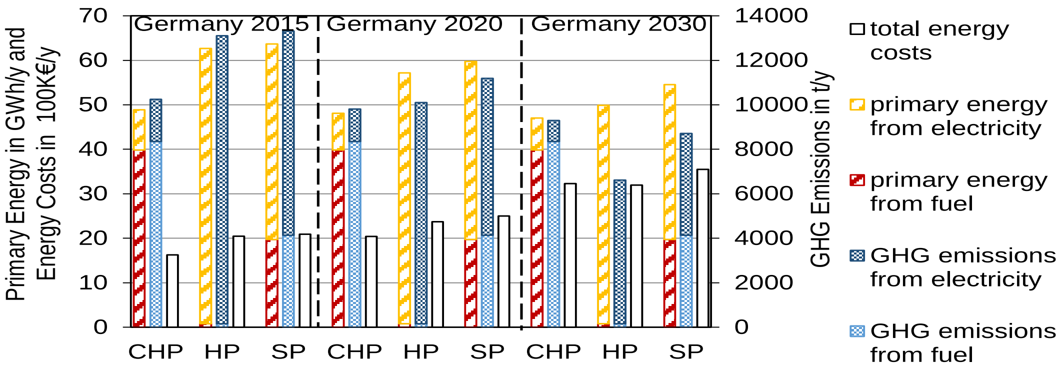

Figure 7: Influence of energy transition in Germany for 2015, 2020, and 2030 including fossil fuel based systems

As expected heat pumps have a major advantage if a country's electricity system has a low GEF and high efficiency. Since the primary energy efficiency of renewables is higher than the one of nuclear power, HP in Norway leads in all categories. In France, HPs can significantly decrease CO_2 emissions but have a negative impact on primary energy efficiency. In the USA and Germany, CHP is in all categories preferable because they have low primary energy efficiency and high GEFs. Figure 7 shows how the performance of various energy supply structures are affected by the energy transition. It indicates that CHP is in case of emissions only one life cycle away from being the highest emitting supply structure. It is expected by 2030 that HPs, which are current unfavourable, will become cost competitive and be the best technology in terms of GHG emissions for a cheese factory in Germany.

7. Conclusions

A spreadsheet tool has been constructed to analyse and optimise energy supply structures for individual sites. This site level analysis is intended to be part of many improvements throughout the entire energy supply chain. A case study of a cheese factory shows the site location and the long-term view of the make-up of national energy systems greatly affects the performance and preference of implementing different energy supply technologies, such as Combined Heat and Power, Steam boilers, and Heat Pumps. The tool requires basic parameters that describe a factory's the energy demand for each medium. Pinch Analysis link into the tool by providing accurate targets for utility demand.

At present the tool provides a static analysis that leads to good results and the work of implementing heat pumps will be continued. Further investigations will be taken with a dynamic MATLAB®/Simulink® model respecting load curves and weather dependency.

References

Becidan M., Wand L., Fosusm M., Midtbust H.O., Stuen J., Bakken J., Evensen, E., 2015, Norwegian Waste-to-Energy (WtE) in 2030: Challanges and Opportunities, Chemical Engineering Transactions, 43, 2401–2406, DOI: 10.3303/CET1543401.

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), 2598-2508, DOI: 10.1021/ie4033999.

Blumberge D., Cimdina G., Timma L., Blumberga A., Rosa M., 2014, Green Energy Strategy 2050 for Latvia: a Pathway towards a Low Carbon Society, Chemical Engineering Transactions, 39, 1507–1512, DOI: 10.3303/CET1439252.

Department of Energy & Climate Change, 2015, Industrial electricity prices in the IEA, <www.gov.uk/government/statistical-data-sets/international-industrial-energy-prices>, accessed 24.03.2016.

Effenberger H., 2000, Dampferzeuger (Steam Generators), Springer-Verlag, Heidelberg (in German).

Fuentes-Cortés L., Ponce-Ortega J., Nápoles-Rivera F., Serna-González M., El-Halwagi M., 2015, Optimal Design of Energy Supply Systems for Housing Complexes Using Multiple Cogeneration Technologies, Chemical Engineering Transactions, 45, 415–420, DOI: 10.3303/CET1545070.

Gerhardt N., Sandau F. Scholz A., Hahn H., Schumacher P., Sager C., Bergk F., Kämper C., Knörr W., Kräck J., Lambrecht U., Antoni O., Hilpert J., Merkel K., Müller T., 2015, Interaktion EE-Strom, Wärme und Verkehr (Interactions of renewable generated electricity, thermal energy and transport), Kassel, <www.energiesystemtechnik.iwes.fraunhofer.de/content/dam/iwes-neu/energiesystemtechnik/de/ Dokumente Veroeffentlichungen/2015/Interaktion_EEStrom_Waerme_Verkehr_Endbericht.pdf>, accessed 18.03.2016 (in German).

Ishak S., Hshim H., Muis Z., 2015, Optimal Low Carbon Cement Production Cost via Co-Processing and Carbon Capture and Storage, Chemical Engineering Transactions, 45, 295–300

Kemp, I. C., 2007, Pinch analysis and process integration a user guide on process integration for the efficient use of energy, Butterworth-Heinemann, Oxford.

Linhoff, B., 1979, Thermodynamic Analysis in the Design of Process Networks, Ph.D. Thesis, University of Leeds.

Mauch W., Corradini R., Wiesmeyer K., Schwentzek M., 2010, Methods of allocation for specific CO2-Emissions of electricity and heat of CHP), Energiewirtschaftliche Tagesfragen, 9, 12-14 (in German).

Nitsch J., Pregger T., Scholz Y., Naegler T., Sterner M., Gerhardt N., 2010, Leitstudie 2010 (Pilot study from Federal Ministry of Environment). BMU - FKZ 03MAP146, DLR, Fraunhofer IWES, IfnE (in German).

Nizami A.-S., Rhean M., Ouda O., Shahzad K., Sadef Y., Ismail I., 2015, An Argument for Developing Waste-to-Energy Technologies in Saudi Arabia, Chemical Engineering Transactions, 45, 337–341, DOI: 10.3303/CET1545057

Pehnt M., 2010, Energy efficiency, a guide book, Springer-Verlag, Berlin, Germany (in German).

Schaumann G., Schmitz W.K., 2010, Kraft-Wärme-Kopplung (Combined Heat and Power), Springer-Verlag, Heidelberg (in German).