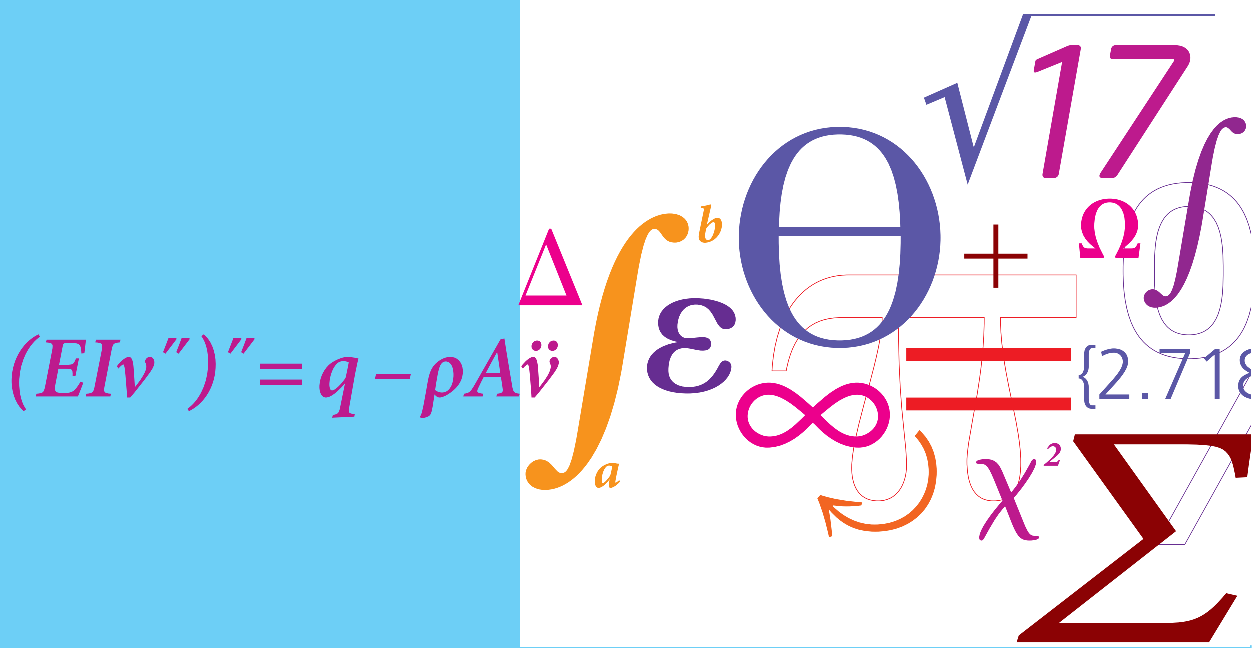
Energy efficiency in the industry: A study of the methods, potentials and interactions with the energy system

PhD Thesis



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A study of the methods, potentials and interactions with the energy system

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by
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under suggestion of:
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Preface

The present thesis was prepared at the Section of Thermal Energy, Department of Mechanical Engineering, Technical University of Denmark (DTU). It is submitted as a partial fulfilment of the requirements for the degree of Doctor of Philosophy. This version of the thesis includes minor revisions, which were implemented following the suggestions of the examiners.

The work was carried out for three years, from December 2014 to March 2018, under supervision of Professor Brian Elmegaard (DTU) and co-supervision of Researcher Tuong-Van Nguyen (DTU) and Head of Industry Fridolin Müller Holm (Viegeand Maagøe A/S, VMAS).

An external research stay was undertaken at the Forschungsgesellschaft für Energiewirtschaft in Munich, Germany, under guidance of Dr.-Ing. Anna Gruber and Dr.-Ing. Serafin von Roon, from November 2016 to February 2017.

The funding was ensured by the Technical University of Denmark and within the project THERMCYC funded by the Danish Council for Strategic Research in Sustainable Energy and Environment. Support was also received from the Otto Mønsted A/S Fond in the frame of the SDEWES 2015, ESCAPE 2016 and ECOS 2017 conferences and of the PhD external stay in Germany.

Copenhagen, March 2018 Fabian Bühler

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Abstract

The industry sector has an important role in decarbonising the energy system, as recognised by the European Commission in their 2050 roadmap to a low carbon economy. It has a high share in the final energy use of the European Union, which in 2016 relied heavily on fossil fuels. A shift to a more sustainable energy use is thus needed, requiring both an increased share of renewable energy and a reduction in energy use.

In this thesis the manufacturing industry was analysed to show its potential to improve energy use on an energy system and process level. For this purpose the inefficiencies of the industry sector of Denmark were taken as an example and quantified using energy and exergy methods. The developed models were used to quantify the amount of industrial excess heat. Based on these mappings, the potential for recovering and exploiting excess heat was analysed, which required the development of new methods to locate potentials. The methods included spatial, temporal and economic elements to have a realistic assessment of national potentials. This was complemented with multiple case studies, for which the model input uncertainties were taken into account. The second part of the thesis considered specific production processes and methods for assessing them. For the case study of a milk powder production system, different engineering and advanced thermodynamic methods were used for the analysis. The different methods, which include pinch and exergy analyses, located and quantified different optimisation potentials, which were compared against each other. At last, specific optimisation opportunities were identified and evaluated. These consisted of a retrofit heat exchanger network and the integration of heat pumps and solar thermal energy.

The results show that the energy efficiency of the Danish manufacturing industry was 80 % and only 72 % when taking the utility system into account. The losses are often in the form of recoverable excess heat. It was found that 1.5 TWh of excess heat could be cost-effectively used for district heating. The tool developed for the case studies enables to overcome some of the barriers for the utilisation of excess heat. It assesses heat sources and possible uses considering the uncertainties and determining important model parameters.

The analysis of the dairy factory resulted in potentials for improvement and highlighted merits and drawbacks of the applied methods. The advanced methods allowed for a thorough analysis of components and interactions amongst each other, the engineering approach is quick to indicate possible improvement but requires experience. The specific improvement suggestions show that it is technically and economically possible to reduce energy use by means of heat integration and to partly replace the hot and cold utilities with more sustainable ones.

Resumé

Industrien spiller en vigtig rolle i at reducere udledningen af drivhusgasser, som blev anerkende af Europæisk Kommission i deres klima strategi indtil 2050. Industrien har en stor andel i den Europæiske Unions energiforbrug, som i 2016 var stærkt afhængig af fossile brændsler. Det er derfor nødvendigt med et skift til et mere bæredygtigt forbrug, hvilket kræver en større andel vedvarende energi samt en reduktion af energiforbruget.

Denne afhandling har analyseret den industrielle sektor, for at vise reduktionspotentialet for energiforbruget på både energisystem og procesniveau. Af den grund blev ineffektiviteten i industrisektoren, med Danmark som eksempel, kvantificeret ved brug af energi- og exergimetoder. De udviklede modeller blev brugt til at kvantificere mængden af overskudsvarme fra industrien. Baseret på disse kortlægninger, blev potentialet for at genvinde overskudsvarme analyseret og metoder udviklet. Disse metoder inkluderede geografiske, tidsmæssige, økonomiske og usikkerheds forhold og blev anvendt på forskellige case studier. Anden del af afhandlingen betragter specifikke produktionsprocesser og metoder til at analysere disse. Forskellige praktiske og avancerede termodynamiske metoder blev anvendt til at analyser et mælkepulver-produktionssystem. De forskellige metoder, som inkluderer pinch- og exergianalyser, lokaliserede og kvantificerede forskellige forbedringspotentialer, der efterfølgende blev sammenlignet med hinanden. Til sidst blev specifikke forbedringsmuligheder identificeret, disse bestod af nye varmevekslernetværk, integration af varmepumper og solvarmeanlæg.

Denne afhandling har påvist at den danske industrisektor har en energi effektivitet af 80 % , som reduceres til 72 % når man også inkludere forsyningen. I nogen tilfælde resulterer den i overskudsvarme, der med økonomisk fordel kunne blive brugt til produktion af fjernvarme. Potentialet vurderes til 1.5 TWh fjernvarme i denne arbejd. For at overvinde barrierer i forbindelse med udnyttelse af overskudsvarme, er der blevet udviklet et værktøj, som kan evaluere varmekilder og mulige aftagere ved at betragte usikkerheder og ved at identificere vigtige model parametre. Analysen af mælkepulverfabrikken resulterede i et estimeret forbedringspotentiale og har fremhævet fordel og ulemper af de anvendt metoder. De avancerede termodynamiske metoder tillader en grundig analyse af komponenter og sammenspillet mellem disse, mens de praktiske tilgange hurtigt kan identificere mulige forbedringer, men samtidig kræver stor erfaringen. De specifikke forbedringsforslag viser at det er økonomisk og teknisk mulig at reducere energiforbruget ved brug af processintegration og ved delvist at erstatte forsyningen af varme og kulde med mere bæredygtige løsninger.

Papers and Presentations

Part of the work performed during the PhD project resulted in peer-reviewed publications and presentations, which are listed hereafter in the order of acceptance and by category. They are directly or indirectly related to the main topics of this thesis.

Peer Reviewed Journal Publications

- [P1] **Fabian Bühler**, Tuong-Van Nguyen and Brian Elmegaard. Energy and Exergy Analyses of the Danish Industry Sector. Applied Energy, Vol. 184, p. 1447–1459, 2016.
- [P2] Anish Modi, **Fabian Bühler**, Jesper Graa Andreasen and Frederik Haglind. A review of solar energy based heat and power generation systems. Renewable & Sustainable Energy Reviews, Vol. 67, p. 1047-1064, 2017.
- [P3] **Fabian Bühler**, Stefan Petrović, Kenneth Karlsson and Brian Elmegaard. Industrial excess heat for district heating in Denmark. Applied Energy, Vol. 205, p. 991-1001, 2017.
- [P4] **Fabian Bühler**, Stefan Petrović, Fridolin Müller Holm, Kenneth Karlsson and Brian Elmegaard. Spatiotemporal and economic analysis of industrial excess heat as a resource for district heating. Energy, Vol. 151, p. 715-728, 2018.
- [P5] **Fabian Bühler**, Andrej Guminski, Anna Gruber, Tuong-Van Nguyen, Serafin von Roon and Brian Elmegaard. Evaluation of Energy Saving Potentials, Costs and Uncertainties in the Chemical Industry in Germany. Applied Energy, Vol. 228, p. 2037-2049, 2018.
- [P6] **Fabian Bühler**, Stefan Petrović, Torben Ommen, Fridolin Müller Holm, Henrik Pieper and Brian Elmegaard. Identification and Evaluation of Cases for Excess Heat Utilisation using GIS. Energies, Vol. 11(4), pp. 762, 2018.
- [P7] **Fabian Bühler**, Tuong-Van Nguyen, Jonas Kjær Jensen, Fridolin Müller Holm and Brian Elmegaard. Energy, Exergy and Advanced Exergy Analysis of Milk Powder Production. Energy, Vol. 162, p. 576-592, 2018.
- [P8] Stefan Petrović, **Fabian Bühler**, Mikkel Simonsen, Kenneth Karlsson and Brian Elmegaard. Industrial Excess Heat in TIMES-DK. 2018. [To be submitted].

Peer Reviewed Conference Publications

[C1] **Fabian Bühler**, Fridolin Müller Holm, Baijia Huang, Jesper Graa Andreasen and Brian Elmegaard. Mapping of low temperature heat sources in Denmark. Proceedings of ECOS 2015, the 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. Pau, France.

[C2] **Fabian Bühler**, Tuong-Van Nguyen and Brian Elmegaard. Energy and Exergy Analysis of the Danish Industry Sector. Proceedings of SDEWES 2015, the 10th Conference on Sustainable Development of Energy, Water and Environment Systems. International Centre for Sustainable Development of Energy, Water and Environment Systems. Dubrovnik, Croatia.

[C3] Riccardo Bergamini, Tuong-Van Nguyen, **Fabian Bühler** and Brian Elmegaard. Development of a Simplified Process Integration Methodology for application in Medium-Size Industries. Proceedings of ECOS 2016, the 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. Portorož, Slovenia.

[C4] **Fabian Bühler**, Tuong-Van Nguyen and Brian Elmegaard. Sustainable Production of Asphalt using Biomass as Primary Process Fuel. Chemical Engineering Transactions Proceedings of PRES 2016, the 19th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction. Vol. 52, p. 685-690, 2016. Prague, Czech Republic.

[C5] **Fabian Bühler**, Tuong-Van Nguyen, Jonas Kjær Jensen and Brian Elmegaard. Energy, Exergy and Advanced Exergy Analysis of a Milk Processing Factory. Proceedings of ECOS 2016, the 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. Portorož, Slovenia.

[C6] **Fabian Bühler**, Tuong-Van Nguyen, Brian Elmegaard and Anish Modi. Process and Economic Optimisation of a Milk Processing Plant with Solar Thermal Energy. Computer Aided Chemical Engineering - Proceedings of ESCAPE 2016, the 26th European Symposium on Computer Aided Process Engineering. Elsevier Science, Vol. 38, p. 1347–1352, 2016. Portorož, Slovenia.

[C7] Benjamin Zühlsdorf, **Fabian Bühler**, Roberta Mancini, Stefano Cignitti and Brian Elmegaard. High Temperature Heat Pump Integration using Zeotropic Working Fluids for Spray Drying Facilities. Proceedings of the 12th IEA Heat Pump Conference 2017.

[C8] **Fabian Bühler**, Andrej Guminski, Anna Gruber, Serafin von Roon and Brian Elmegaard. Energy Saving Potential, Costs and Uncertainties in the Industry: A Case Study of the Chemical Industry in Germany. Proceedings of ECOS 2017, the 30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. San Diego, USA.

[C9] **Fabian Bühler**, Stefan Petrović, Torben Ommen, Fridolin Müller Holm and Brian Elmegaard. Identification of Excess Heat Utilisation Potential using GIS: Analysis of Case Studies for Denmark. Proceedings of ECOS 2017, the 30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. San Diego, USA.

Technical Reports

[T1] Baijia Huang, **Fabian Bühler**, Fridolin Müller Holm. Industrial Energy Mapping: THERMCYC WP6. Technical University of Denmark, 2015.

[T2] **Fabian Bühler**,Ulrik Vølcker and Fridolin Müller Holm. Energy Consumers and Technology: THERMCYC WP6. Technical University of Denmark, 2018. [Under revision].

Abstracts and other publications

[O1] **Fabian Bühler**, Tuong-Van Nguyen and Brian Elmegaard. Recovery Potential and Emissions of Excess Heat in Denmark. Abstract and Poster at Sustain-ATV Conference, 2015. Kgs. Lyngby, Denmark.

[O2] Benjamin Zühlsdorf, Roberta Mancini, **Fabian Bühler**, Jesper Graa Andreasen, Andrea Meroni, Brian Elmegaard and Fredrik Haglind. THERMCYC – Advanced Thermodynamic Cycles Utilizing Low Temperature Heat Sources. Abstract and Poster at Sustain-ATV Conference, 2016. Kgs. Lyngby, Denmark.

[O3] Stefano Cignitti, Jerome Frutiger, Benjamin Zühlsdorf, **Fabian Bühler**, Jesper Graa Andreasen, Fridolin Müller Holm, Fredrik Haglind, Brian Elmegaard, Jens Abildskov, Gürkan Sin and John Woodley. Forbedring af industrielle processers energieffektivitet. Dansk Kemi, Vol. 97, No. 10 p. 10-12, 2016.

[O4] **Fabian Bühler**, Brian Elmegaard and Fridolin Müller Holm. Energieffektivitet ved udnyttelse af overskudsvarme i industrien . Plus Proces, Vol. 32, No. 1 p. 10-14, 2018.

Contents

Nomenclature

Abbreviations

A	Air in spray drying section
AF	Annuity factor
AFR	Air to fuel ratio
AP	Air to product
B	Gas boiler
BBR	Danish Register of Buildings and Dwellings
C	Cold process stream Cream treatment section
CC	Composite curve
CHP	Combined heat and power
COP	Coefficient of performance
CRF	Capital recovery factor
CU	Cold utility
CVR	Central company register
DC	Direct costs
DH	District heat
DHW	Domestic hot water
DKE	Denmark East
DKK	Dansk krone (Danish Krona)
DKW	Denmark West
DM	Dry matter
DRY	Design Reference Year
E	Product in evaporation section
EE	Elementary effects
EEM	Energy efficiency measure
EH	Excess heat
EPRTR	European Pollutant Release and Transfer Register
ETS	Emission Trading Scheme
EV	Evaporation
G	Gamma
GCC	Grand composite curve
GHG	Greenhouse gas
GIS	Geographic information system
H	Hot process stream
HD	Heating demand
HEN	Heat exchanger network
HEX	Heat exchanger
HP	Heat pump
HRE	Heat recovery equipment
HU	Hot utility
IPCC	Intergovernmental Panel on Climate Change

IRR	Internal rate of return
LHS	Latin hypercube sampling
LHV	Lower heating value, J kg^{-1}
LP	Linear programming
M	Milk treatment section
MC	Monte Carlo
MER	Minimum energy requirement
MILP	Mixed integer linear programming
MINLP	Mixed integer non linear programming
MT	Milk treatment
MVR	Mechanical vapour recompression
N	Normal
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
NPV	Net present value
O&M	Operation and maintenance
OAT	One factor at a time
ORC	Organic Rankine cycle
P	Product in spray drying section
PbT	Payback time
PEC	Purchased Equipment Costs
PP	Production profile
Q	Quartile Quarter
R	Regenerative heat exchanger
RM	Refrigeration cycle
SA	Sensitivity analysis
SC	Self-consumption
SD	Spray drying
SEK	Svensk krone (Swedish Krona)
SiEN	Site energy efficiency, -
SiEX	Site exergy efficiency, -
SME	Small medium enterprise
SRC	Standardised regression coefficient
SyEN	System energy efficiency, -
SyEX	System exergy efficiency, -
TCI	Total capital investment
TES	Thermal Energy Storage
TVR	Thermal vapour recompression
U	Uniform
VE	Vapour in evaporation section
WWT	Waste water treatment
yr	Year

Greek letters

α	Carbon atoms, - Azimuth angle, -
β	Hydrogen atoms, -
χ	Molar fraction, -
ΔT	Temperature difference, K
η	Energy efficiency, -
γ	Exponent, -
λ	Air to fuel equivalence ratio, -
μ	Chemical potential,- Mean value, -
$\mu*$	Absolute mean, -

ϕ	Chemical exergy to LHV ratio, -
ψ	Exergy efficiency, -
σ	Standard deviation, -
ε	Exergy efficiency, -
ε^*	Modified exergy efficiency, -
ζ	Angle or elevation, -

Roman letters

A	Area, m^2
a	Shape parameter, -
b	Inverse scale parameter, -
C	Costs, €
c	Specific costs, € MWh^{-1}
$\overline{c}$	Weighted mean specific costs, € MWh^{-1}
cp	Specific heat capacity, $kJ\,kg^{-1}\,K^{-1}$
CRF	Capital recovery factor, -
d	Discount rate, %
E	Earnings, €
e	Specific exergy, $J\,kg^{-1}$
$\dot{E}$	Exergy rate, W
h	Specific enthalpy, $J\,kg^{-1}$ Heat transfer coefficient, $W\,m^{-2}\,K^{-1}$ Operating hours, hours
$\dot{H}$	Enthalpy rate, W
I	Investment costs, € Solar irradiation, $W\,m^{-2}$
i	Interest rate, %
j	Annual price increase, %
k	Overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
LMTD	Logarithmic Mean Temperature Difference, K
$\dot{m}$	Mass flow rate, $kg\,s^{-1}$
N	Lifetime, years Number,-
n	Lifetime, years
p	Pressure, Pa Pertubation factor, -
Q	Heat, MWh
$\dot{Q}$	Heat rate, W
R	Revenue, €
r	Repetitions, -
S	Share, %
s	Specific entropy, $J\,kg^{-1}\,K^{-1}$
SF	Solar fraction, -
T	Temperature, °C
U	Internal energy, J
V	Volume, m^3
$\dot{W}$	Power, W
X	Model input, -
$\bar{x}$	Molar fraction, -
Y	Model output, -
y^*	Exergy destruction ratio, -
z	Cost constant, -

Subscripts

0	Environmental state
00	Dead state
air	Air

Conc	Concentrate
D	Destruction
Demand	Demand limitation
DH	District heat
Di	Diffuser
DIFF	Diffuse
DIR	Direct
E	Equipment
EH	Excess heat
el	Electric
F	Fuel
f	Fixed
gen	Generator area
GRO	Ground
H	Heat delivered
H	Heating
HD	Heating demand
hor	Horizontal
HP	Heat pump
i	i^{th} fuel, -
in	Inflow
infl	Inflation
is	Isentropic
j	j^{th} process, -
k	Thermal stream Storage unit Component
L	Loss Loan
lm	Logarithmic mean
m	Mean difference
min	Minimum
N	Nozzle
n	year
NG	Natural gas
notDH	Not district heating
o	Optical
OM	Operation and Maintenance
out	Outflow
P	Product
p	Industrial site
Pipe	Transmission pipelines
pr	Process
q	District heating area
R	Return
ref	Reference
S	Supply
sat	Saturation
Stoich	Stoichiometric
Storage	Heat through storage
Su	Summer
t	Time step
TES	Thermal energy storage
tot	Total
v	Variable

W	Winter

Superscripts

0	Reference year
AV	Avoidable
CH	Chemical
EN	Endogenous
EX	Exogenous
KN	Kinetic
PH	Physical
PT	Potential
Q	Heat transfer
sys	system
UN	Unavoidable
W	Work transfer

1 Introduction

1.1 Background

The use of fossil fuels as primary energy sources is widely seen as the main contributor to global warming because of their high carbon content and associated greenhouse gas emissions. It was acknowledged by most member countries of the United Nations in the 2015 Paris Agreement [1] that climate change is a common concern of humankind. It was further recognised that the sustainable patterns of consumption and production are important in order to combat climate change. The depletion of fossil fuels further requires a shift to renewable and sustainable energy sources. The European Union has defined in its 2050 climate roadmap [2] that greenhouse gas emissions (GHG) should be reduced by 80 % until 2050 compared to the 1990-level. It is further suggested that all sectors need to contribute, although the power, residential and industry sectors are expected to provide the largest contribution in reaching the 2050 aim. Another requirement for the transition is that it has to be affordable and cost-efficient, which can be achieved, amongst other options, by keeping the EU emission trading system a key instrument and accelerating the development and deployment of low-carbon technologies.

There are three main actions which can be taken to reduce greenhouse gas emissions and the dependency on fossil energy carriers: (i) maximizing the resource and energy-efficiency, (ii) switching to low-carbon and optimally renewable energy sources and (iii) deploying large-scale carbon capture. It is crucial to understand and analyse the systems where resources and energy are consumed and depleted, in order to plan and steer future developments.

Energy use in the EU has been overall constant over the last two decades as can be seen in Figure 1.1. During the same time the Gross Domestic Product (GDP) has increased steadily. The EU 2050 energy roadmap [3] sets ten structural changes for energy system transformation. These require very significant energy savings in all decarbonisation scenarios. The primary energy demand needs to drop in a range of 32 % to 41 % by 2050 as compared to peaks in 2005-2006. These significant energy savings will require a stronger decoupling of economic growth and energy consumption as well as strengthened measures in all economic sectors.

Additionally, the share of renewable energies needs to rise substantially, to achieve at least 55 % of the gross final energy use in 2050.

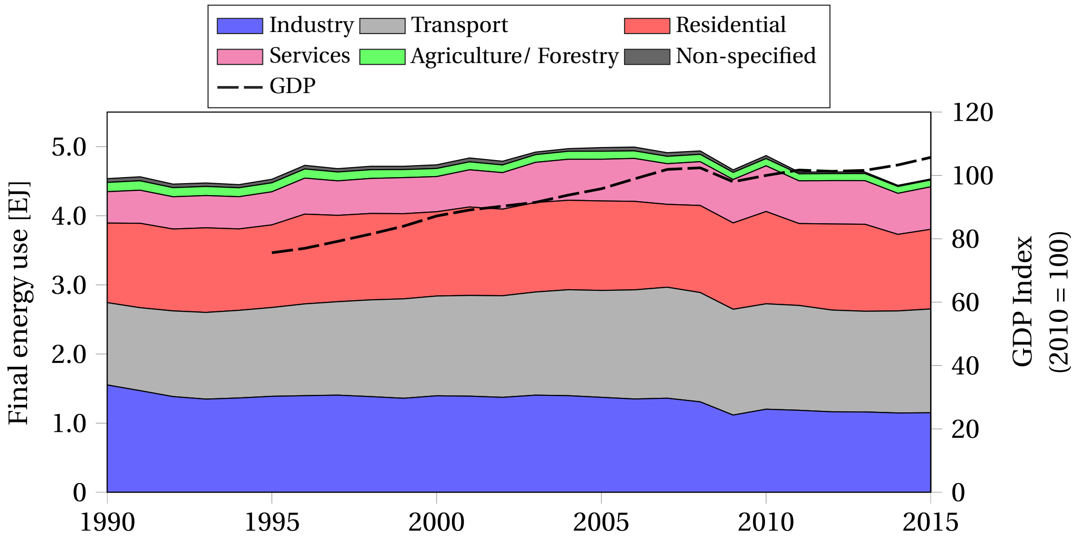


Figure 1.1: Final energy use by sector in the EU28 and index for the gross domestic product (GDP) from 1990 to 2015 [4].

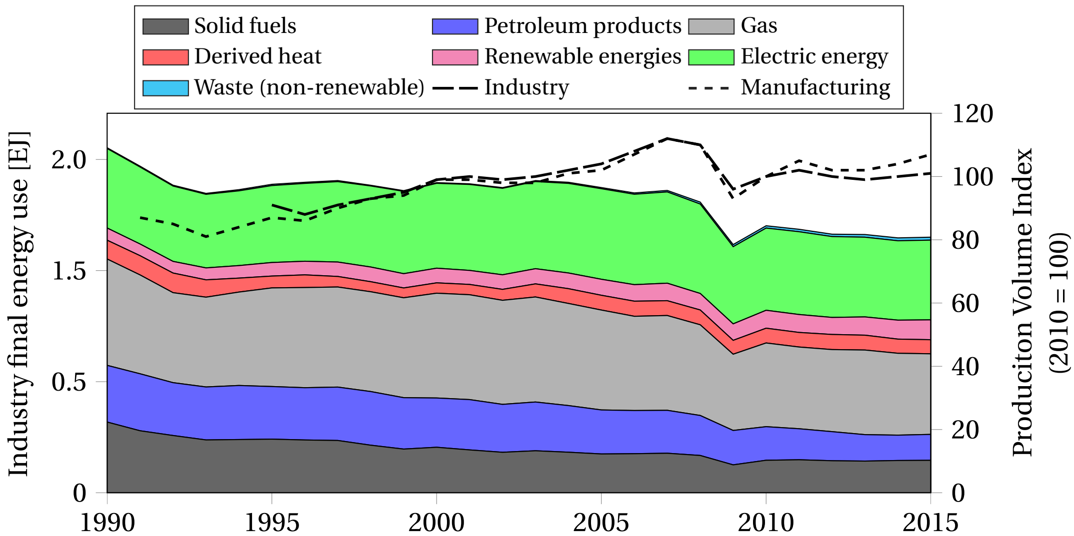


Figure 1.2: Final energy use in the industry by energy type in the EU28 and production volume index for the industry and manufacturing sector from 1990 to 2015 [4].

1.1.1 Industrial energy use and energy efficiency

The industrial sector plays an important role in decarbonising the energy system, as it represents 25 % of the EU final energy use and even 37 % worldwide [5]. Although the share of fossil fuels used in the industry has decreased, more than half of the energy supply of the EU in 2015 still originated directly from fossil fuels, as can be seen in Figure 1.2. The electricity generated in the EU originated with almost 50 % from thermal power plants using fossil fuels [4], further increasing the industries dependency on this resource. The final energy use of the industry has declined over the last decades in the EU, while the growth in production volumes only decelerated. Also on a global scale the energy intensity of the industry has decreased by 30 % between 2000 and 2016 [6]. However, the majority of the energy used in Europe and the rest of the world derives from the direct use of fossil fuels or indirectly through the electricity or heat used.

In Europe, energy efficiency is seen as an important factor in the transition to a sustainable and resource efficient society, as well as one of the most cost-effective ways to reduce GHG emissions [7]. In Denmark, the manufacturing industry accounted for 14 % of the total final energy use in 2015, which is a 22 % decrease compared to 1990 [8]. The trend of reducing energy use and focusing on energy efficiency improvements, not only in manufacturing sector, has started with the first oil crisis in 1973. Since then many policies for the industrial sector, particularly at the beginning of 1990's, have been implemented. Most recently, the energy efficiency obligations for the Danish energy distribution companies affect all end-consumer sectors and, since 2013, an investment subsidy scheme promotes the use of renewable energy and the implementation of energy efficiency measures for industrial processes [9]. Another trend, not only in Denmark, is industrial symbiosis, where industries take a collective approach to exchange materials, energy, water and more, with the aims of maximizing the resource use, minimizing the waste production and opening up new possibilities of obtaining a competitive advantage. This can include the recovery of surplus process heat at one production unit and using it at another one or simply sharing a common utility infrastructure [10]. Industries can also be closely integrated with the energy system, which is the energy demand and supply of other sectors (e.g. residential, utility and service sector). The industry would then not only use energy but also act as an energy supplier. Low temperature excess heat can for example be recovered and delivered to district heating networks. Electricity can also be generated on roof areas of the factory with photovoltaic cells or through combined heat and power plants at the factory [11, 12]. A holistic and integrated approach to industrial energy use can result in new opportunities leading to a more efficient and sustainable use of energy.

1.1.2 Analysis of industrial processes

There exist many cost-efficient opportunities for industrial companies to reduce their energy use while keeping their production at a constant level. In the case of Denmark these cost efficient reductions were estimated to be up to 28 % of the heating demand of the Danish industry in 2009 [13]. However, industrial firms do not always implement cost-effective energy conservation projects for reasons partly explainable by economic (market failure and non-market failure), behavioural and organizational theories [14]. This is also frequently referred to as the energy efficiency gap [15]. In addition, Thollander and Palm [16] mention the energy efficiency gap, the encapsulating energy management and energy policy gap. Industrial energy management is described as being probably the most important element in closing the energy efficiency gap, implying that companies need to take a strategic approach to reduce their total energy use.

Such a strategic approach has many dimensions: an analysis of the industrial plant needs to be performed to quantify the energy use, possible energy savings and surplus heat sources. Based on these measures energy efficiency improvements, renewable energy integration and heat recovery can be developed, optimised and implemented. The analysis starts generally with the collection of factory and process data, measurements and the creation of mass and energy balances. Depending on the industry type and factory size this process can become complex and time-intensive if a complete picture of the process is needed. There are several methods which can be used to find the optimal degree of energy use, detect inefficiencies and suggest improvements of the industrial processes. Pinch analysis, in particular heat integration, is one method used to analyse industrial processes and to develop suggestions for improvement. This method can however be far from engineering practice, does not consider the economic optimal configuration and requires some sort of simplification for complex processes [17]. Also the use of exergy analysis, as an advanced method, is frequently suggested for efficiency optimisation as it is a technical tool in engineering. A wider application of exergy analysis in industrial practice could be expected, however this is generally not the case as noted by Rosen [18]. Some major reasons for this are stated as exergy methods being too complex and results too difficult to interpret by some users, as well as engineers not having reached practicable results. However, Rosen [18] also notes that these are simply barriers to the method, which can be overcome by increasing the application rate of exergy methods in the industry.

Once possible energy efficiency measures are identified, their feasibility has to be assessed. This technical and economic assessment requires a number of assumptions and estimates which are connected with uncertainties and variabilities. The impact of these uncertainties on the outcome of the assessment can have great influence on the decision making process and can be used to identify important system parameters. The developed decision support model should therefore also include information about the uncertainties related to all alternatives, as the certainty of the desired outcome may be a central criterion [19].

1.2 Statement

In this work the term industry refers to the manufacturing of goods and products. This industry consists of industrial sectors in which industrial sites producing similar products are grouped. A schematic of an industrial site is shown in Figure 1.3, creating a product using different inputs and generating different output streams. Output streams are often seen as waste streams, such as excess heat, waste water or solid waste. Each industrial site consists of industrial processes, which transform the input stream to the final product, and the site utility, which provides auxiliary services such as heating, cooling or compressed air. The industrial processes can consist of many different ones, such as heating, evaporation, drying, pressing and so forth. Each process can consist of different components, e.g. multiple heat exchangers for heating a stream or multi-effect evaporators.

The industrial site is, however, not an isolated system, but receives energy services from the energy system (also referred to as utility sector or utility system in this work). It is possible to integrate multiple factories to exchange streams, as described in the previous section, or to use natural renewable sources, e.g. solar or geothermal energy.

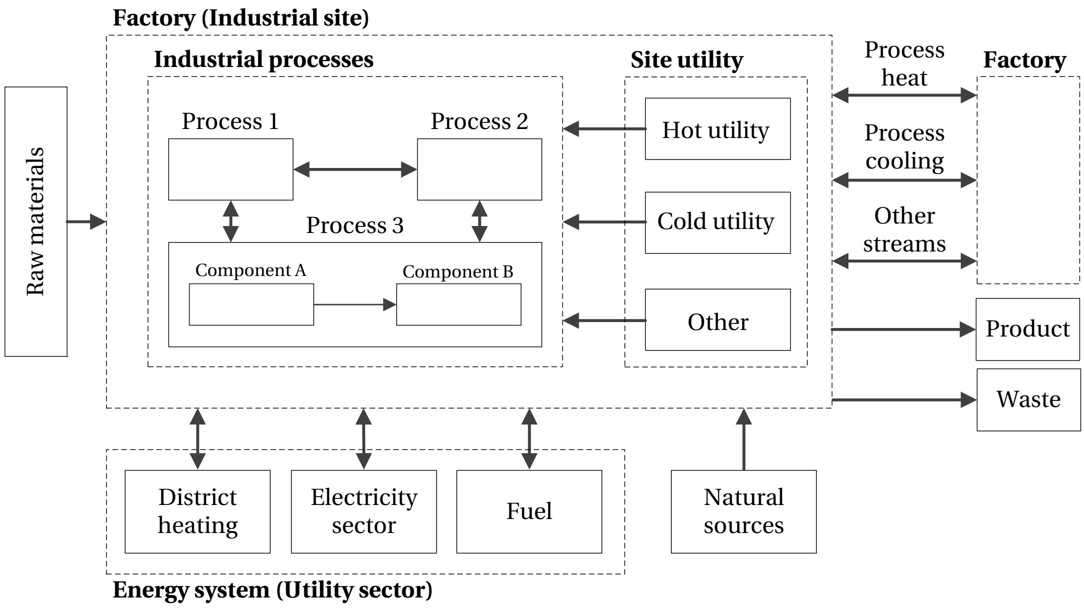


Figure 1.3: System diagram of an embedded factory with the main material and energy flows within and across its system border.

To reach the EU's goal of reducing GHG emissions and thereby contributing to the worldwide efforts to tackle climate change, the industrial sector has to transform its energy use. This transformation has to be done in an integrated way, meaning the industry has to be seen as an incorporated part of the energy system and its surroundings. Energy use in the industry needs to be changed and barriers to these changes need to be overcome. It is further necessary to consider different levels:

(i) On the process level the efficiency has to be increased, which can be done by integrating processes, by increasing the efficiency of the process through a replacement of the whole process or components, or by changing the process set-points.

(ii) On the factory level energy use and demand have to be integrated

(iii) The heating and cooling must be supplied in a sustainable way

(iv) The factory has to be integrated with its surrounding, where it does not only use energy resource but can also supply them.

This work is based on the conception that the levels mentioned above are not sufficiently exploited at most industrial sites. This leads to three hypotheses which are relevant for this work, namely:

(i) Industrial sites and processes still have a potential to be designed, retrofitted and operated to run with a reduced amount of input energy while providing the same amount of output (product).

(ii) Many industries have waste streams, in particular excess heat, which are often unused and can present a valuable resource. These streams can be integrated in a process at the industrial site or exported to the energy system or other factories.

(iii) To support and inform the industry and the utility sector in the necessary developments to accomplish (i) and (ii), in particular with respect to energy efficiency and excess heat utilisation, systematic and practical approaches need to be developed and the possible (saving) potentials need to be determined.

1.2.1 Research questions

The present work aims to complement the current state of research in this field and to answer the following main research questions:

- How can the energy use of the industry as an integrated part of the energy system be assessed?
- Can industrial excess heat be utilised externally and what relevance does it have from an energy system perspective?
- What are the barriers and uncertainties for excess heat utilisation?
- Which methods are suitable and have practical relevance for analysing industrial sites, in particular dairy sites?
- How can the fossil fuel use of an industrial site be changed, while being cost effective and considering the best options?

1.2.2 Objectives

This research has two focus areas, namely the industry of a country or region and the industrial processes themselves. From these areas the main objectives consist in assessing and optimising the industry as an integrated part of the energy system and support this by analysing and optimising specific production processes using advanced thermodynamic methods.

In order to reach the targeted outcome, it is necessary to accomplish several objectives for the sector and process analysis respectively. On the sector level the following objectives can be defined:

- evaluate the energy resource conversion efficiency in the industrial sector
- determine the level of excess heat from industrial processes
- develop a method to analyse the utilisation potential of excess heat for district heating of a region or country
- determine possible barriers to the utilisation of excess heat in a national context
- develop a tool to locate and assess excess heat utilisation projects
- determine the uncertainties and important parameters in excess heat utilisation projects

To support the sectoral findings and case studies, industrial processes need to be analysed in detail using different methods, which have relevance for industry practice. For the given processes, the following objectives can be defined:

- develop models that describe the global behaviour of production systems including the utility supply
- identify the possible system interactions and improvements using multiple methods based on the pinch, energy and exergy concepts
- compare the applicability of these methods under different viewpoints to engineering approaches
- investigate the feasibility of replacing and improving current utility systems

1.2.3 Approach

The present work can be divided into two parts: (i) the sectoral analysis of industrial energy use and excess heat recovery and (ii) the analysis of industrial sites using different thermodynamic methods. The work is to a large degree numerical and no experimental aspects were considered.

The first part of the work deals with the sectoral analysis of industrial energy use, in which Denmark is taken as a case study, considering country-specific conditions (e.g. taxes, policies and existing energy infrastructure). The main findings and recommendations are therefore related to this case study. The methods were to some extent built on data available for Denmark. The data used was to a large degree available from national and European public institutions, as well as utility companies and industry associations. Although the conclusions would be different, the applicability of the proposed methods to other regions and countries is discussed.

The analysis of the industrial case studies is based on data which was obtained through data collection and measurements at the industrial sites or was provided from the industrial partners. The case studies are based on characteristics of one production unit, but the numerical models are generalised to some extent. Steady-state or quasi-steady-state conditions are assumed, and issues related to the dynamic behaviour of the production processes are not taken into consideration.

1.3 Thesis outline

The thesis is build on a number of journal and conference publications, which were published during the project. In the following, an overview of the chapters and their content is given, as well as the publications they are build upon.

Chapter 1 introduces the present project, along with the motivation, statement and outline of this study.

Chapter 2 introduces the main and fundamental methods and concepts applied throughout the thesis.

Chapter 3 presents an energy and exergy analysis of the industry sector which extends previous methods by accounting for exergy losses and the utility system. The chapter is based on the article [P1].

Chapter 4 presents a quantification and analysis of excess heat in Denmark and details the results for the excess heat potential in the industry. The work presented in this chapter is partly based on the article [C1], report [T1] and an extension of the work performed in article [P1].

Chapter 5 presents a method to determine the potential in using industrial excess heat on a national scale, considering spatial, temporal and economic constraints. This chapter includes the work performed in article [P3] and [P4], with the addition of a sensitivity analysis of important parameters.

Chapter 6 presents a tool and a detailed case study evaluation for different excess heat utilisation pathways. The chapter is based on article [P6].

Chapter 7 first presents the case study of a milk powder production facility, which is then analysed using different methods, in particular engineering, pinch and exergy analysis, to identify inefficiencies and to compare the methods in regard to their applicability in industrial practice. The chapter is based on article [P7].

Chapter 8 based on the dairy case study, opportunities for process, solar and heat pump integration are evaluated based on technical and economic indicators. The integration of solar thermal energy is based on a modified model described in article [C6] and part of the heat pump integration is based on article [C7].

Chapter 9 describes the barriers to energy efficiency measures in the industry, in particular excess heat, based on a literature review. The barriers are discussed and complemented with interviews to describe and to evaluate the situation in Denmark.

Chapter 10 concludes the present thesis, summarising the main findings of this work and pinpointing possibilities for future research.

2 Methods

2.1 Introduction

This work investigated the specific case of the manufacturing industry. Different parts of it were considered and interactions with other systems were included. The created models ranged from energy-end use models of manufacturing industries, such as sugar, dairy and pharmaceutical industries, to models of components, such as evaporators, heat exchanger and hot utilities.

The different elements of the manufacturing industry were modelled, analysed, compared and optimised. This required foremost a systematic methodology and the application of different methods. The main methods, which were fundamental to this work and were applied throughout the thesis are presented in the following sections. The approaches, methodologies and methods, which were primarily used for specific analyses, are presented in the respective chapters. For each method the theoretical background and areas of applications are given.

2.2 Energy analysis

The First Law of Thermodynamics states that energy can be transformed, but can neither be created nor destroyed. This however does not describe the direction of the processes taking place, namely the reversibility of thermodynamic processes. To take this into account, the Second Law of Thermodynamics is used, which is stated in Section 2.5.

The energy interactions of a closed system can be described with Eq. 2.1. The amount of heat dQ is equal to the internal energy dE of the system and the work dW. For a transformation of energy, to define Q, the state functions at the beginning and the end of the transformation have to be known [20].

$$\mathrm{d}Q = \mathrm{d}E + \mathrm{d}W \tag{2.1}$$

2.2.1 Energy balance

As stated by the 1st law of thermodynamics, energy may be stored, transformed from one form to another (e.g. from mechanical to electrical), but can neither be created nor destroyed. For an open system, energy can be transferred in and out of the system under study with streams of matter, heat and work. In this work, changes in kinetic (velocities) and potential (heights) energies are not considered, which implies that the energy balance are in steady-state conditions. This is represented in Figure 2.1, where a control volume with one inlet and one outlet is shown.

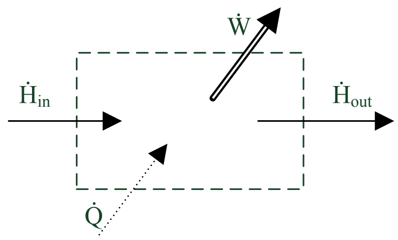


Figure 2.1: Control volume with one inlet and one outlet at steady state adopted from Bejan et al. [21]

Heat can be added to the system and work can be performed. This can be expressed in a rate from in Eq. 2.2 and 2.3.

$$\sum_{\text{in}} \dot{H}_{\text{in}} - \sum_{\text{out}} \dot{H}_{\text{out}} + \sum_{k} \dot{Q}_k - \dot{W} = 0 \tag{2.2}$$

$$\sum_{\text{in}} \dot{m}_{\text{in}} h_{\text{in}} - \sum_{\text{out}} \dot{m}_{\text{out}} h_{\text{out}} + \sum_{k} \dot{Q}_k - \dot{W} = 0 \tag{2.3}$$

The energy flow associated with a stream of matter is denoted as $\dot{H}$, the specific enthalpy of a material stream as h and the mass flow rate of the corresponding stream as $\dot{m}$. The subscripts in and out indicate in- and outflowing streams while $\dot{Q}$ and $\dot{W}$ denote the heat and work rates exchanged with the surroundings. These energy balances are used to analyse different systems throughout this work. Energy analyses are in this context relevant for tracking the energy flows and the transformation of one form of energy to another across different systems.

2.3 Pinch analysis and process integration

The basis for pinch analysis was done by Linnhoff and Flower [22], who created a model for the systematic generation of energy optimised heat exchanger networks. The basis for the pinch analysis is data on the process streams requiring heating or cooling in some form. These process operations are referred to as hot (requiring cooling) and cold (requiring heating) streams. Pinch analysis is at first used to set energy targets for a processing plant, respecting the 2nd law of thermodynamics and can then be used to design a heat exchanger network (HEN) using the minimum amount of external heating cooling, by integrating the hot and cold process streams. In this work, pinch analysis was used in Chapter 7 and 10, where more information about the applied method can be found.

2.3.1 Approach to pinch analysis

The general approach and main steps to pinch analysis in process integration study is as follows [23]:

(i) Retrieving data for the process streams, in particular temperatures and heat capacity rates

(ii) Selecting a minimum temperature difference ΔT_{min} for the whole system or individual ones for the streams. The minimum temperature difference describes the heat potential in the heat exchangers and sets the amount of maximum heat recovery. It can also limit the size of the heat exchanger if there are volume or weight constraints.

(iii) Locating the pinch point and determining the energy targets, which are the potential for heat recovery and the minimum demands for heating and cooling utilities.

(iv) Designing a heat exchanger network which achieves the established energy targets

(v) Analysis of system improvements with respect to utilities and recovery of excess heat

Once the necessary data has been retrieved through measurements and available process information, the hot and cold streams can be visualised in composite curves. To do so a temperature enthalpy diagram is created where the heat capacity of all hot streams is added over a temperature range. This is also done for the cold streams [23]. From the composite curve it is now possible to determine the minimum heating and cooling requirement of the network (Figure 2.2a). The minimum temperature difference ΔT_{min} can be chosen to shift the cold and hot composite curve. The choice of ΔT_{min} in a two stream problem, sets the amount of maximum heat recovery. Furthermore the selection of ΔT_{min} also influences the capital costs required to achieve the energy target. The point where both curves are the closest together is referred to as the pinch point. It is possible to design a HEN for the streams with a minimum amount of external heating and cooling, where the ΔT_{min} is only required for heat exchangers located around this pinch point. The real value for ΔT_{min} is found by the overall heat transfer coefficients and the geometry of the individual heat exchanger. In the design of the HEN, it is thus further not necessary to provide external cooling above and external heating below the pinch point.

The composite curves set the energy targets but are based on graphical constructions [24]. To calculate the energy target directly the problem table algorithm can be used. To do so, it is important to note that the hot and cold streams are always at least by ΔT_{min} apart. This is done by shifting the temperatures of the hot and cold curve by $1/2\Delta T_{\text{min}}$. The shifted streams are then added into a stream population to find the temperature intervals and for each temperature interval the heat balance is calculated [24, p. 367].

By creating a problem table and in a second step eliminating all negative heat values, by adding the hot utility at the top of the table, the minimum external heating and cooling demands are found. In addition it is possible to find the pinch point. This point is in the temperature interval where the heat flow is equal to zero. The pinch point divides the system into two sub-systems: a heat sink (above the pinch point) where external heating is required and a heat source (below the pinch) where external cooling is required. When designing a heat exchanger network, no heat transfer across the pinch point should occur as this would increase either the external heating or cooling demand. From the number of streams above and below the pinch point, it is possible to calculate the minimum number of heat exchangers required to fulfil the minimum demand.

By plotting the utility requirement versus the shifted temperature, the grand composite curve is obtained, as shown for an example case in Figure 2.2. This curve shows the difference between the heat available from the hot streams and the heat required by the cold streams relative to the pinch at a given shifted temperature [23]. Overall the grand composite curve is a useful tool to find the optimal type and placement of utilities for the system. According to Kemp [23] the minimum number of heat exchangers is found as the sum of number of streams N_{streams} and number of utilities N_{utility} below and above the pinch point with Eq. 2.4.

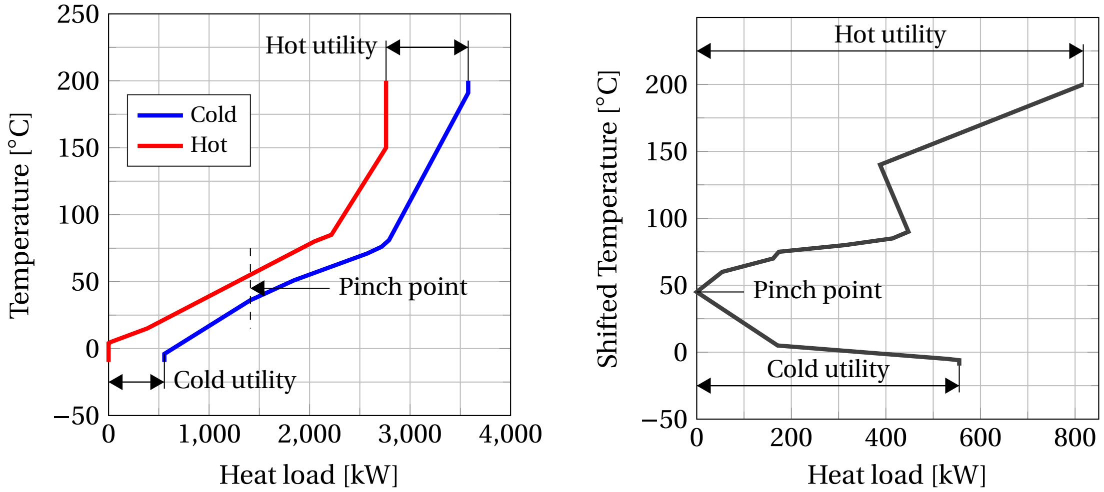
$$N_{\text{min}} = \left(N_{\text{streams}} + N_{\text{utility}} - 1\right)_{\text{below}} + \left(N_{\text{streams}} + N_{\text{utility}} - 1\right)_{\text{above}} \tag{2.4}$$

Besides the energy targeting, other targeting methods exist and can be included in the overall analysis of the system. It is possible to target the capital and total costs of the system or the number of units, heat exchange area and pressure drop [23, 24]. The capital cost targeting consists of several elements which are related to the heat exchangers.

2.3.2 Total site integration

When performing a pinch analysis only on a single process basis, problems can arise when considering the utilities and opportunities for heat recovery may be neglected. Dhole and Linnhoff [25] introduced the total site integration, considering larger systems in which different processes can exchange heat and accounting for possible restrictions. With this method a heat source and a heat sink profile is created [26]. By integrating a number of processes via the steam system, additional inter-process heat recovery can be achieved by using the total site profiles as guides [27].

The modified grand composite curve for the total site is created based on the processes curves, from which the "pockets" are replaced by vertical lines [25]. The source and sink (or hot and



(a) CC

(b) GCC

Figure 2.2: Example of composite curves (a) and a grand composite curve (b) for a minimum temperature difference of 10 K.

cold) elements are shifted by $1/2\Delta T_{min}$ and the single processes are added to a total site grand composite curve. With the modified GCC the placement of the utility system can now be optimised and additional heat recovery option can be found.

2.3.3 Mathematical programming

The pinch analysis has several drawbacks, such as not having an explicit procedure for deriving the configuration of HEN and the HEN solution may not be optimal as the utility and heat exchanger area costs are not directly considered. As described by Klemeš and Kravanja [28], Pinch analysis is useful in generating ideas based on engineering creativity, while the main role of mathematical programming is to further develop those ideas and to generate others by expressing them in mathematical terms. These mathematical terms are then solved to find an optimal and feasible solution for a complex problem.

There are several approaches to mathematical programming that can be classified into sequential synthesis and simultaneous synthesis methods [29]. The sequential approach divides the system into several sub-problems, often into intervals based on the temperature. It is then solved sequentially in three steps:

- Minimum utility cost
- Minimum number of units
- Minimum investment costs

The minimum utility costs can be found by linear programming (LP) using for example transshipment models [30, 31]. These transshipment models can be further extended to constrain undesirable matches. The second sequence can be solved by constructing a cascade diagram for the mixed integer linear program (MILP) transshipment model. At the end the minimum investment costs are found using a superstructure for each match, which was predicted by the MILP model. A superstructure is constructed so that it includes all the possible and feasible process structures, which are in this case all matches obtained by the MILP model.

The heat exchanger network can also be obtained by simultaneous HEN synthesis, where the optimal HEN is found without the decomposition of the problem [29]. The used methods are primarily of MINLP formulations, which are simplified to find solutions to complex problems. On of the approaches used in this work, is the one by Yee and Grossmann [32], where costs and matches are simultaneously optimised. The solutions which are obtained by the simultaneous approach are better than the ones from the sequential approach, as the optimal trade-offs between energy consumption, number of heat exchangers and their costs are taken into account. However, this approach requires more computational time and the initial guesses with respect to costs can have great influence.

Other applications of the pinch method

Besides energy, pinch methods can also be applied to other components of industrial plants. A brief overview is given in the following of other applications based on Friedler [27]. El-Halwagi and Manousiouthakis [33] describes a method on how to synthesize mass-exchange networks. In this method the pinch point of the mass exchange is found in a similar method to the pinch analysis for energy streams. Instead of considering the transfer from hot to cold streams, the mass transfer from rich to lean streams is analysed. For each stream a start and target composition is defined, which is constraint by e.g. physical, economic, technical or environmental properties. This method is for example used for the process of removal of acidic impurities of coke-oven gas [33].

Wang and Smith [34] introduced a method for the minimisation of waste water from the process industry. This method is based on a reduction in water consumption by re-using, regenerating and recycling water. This is often referred to as water-pinch.

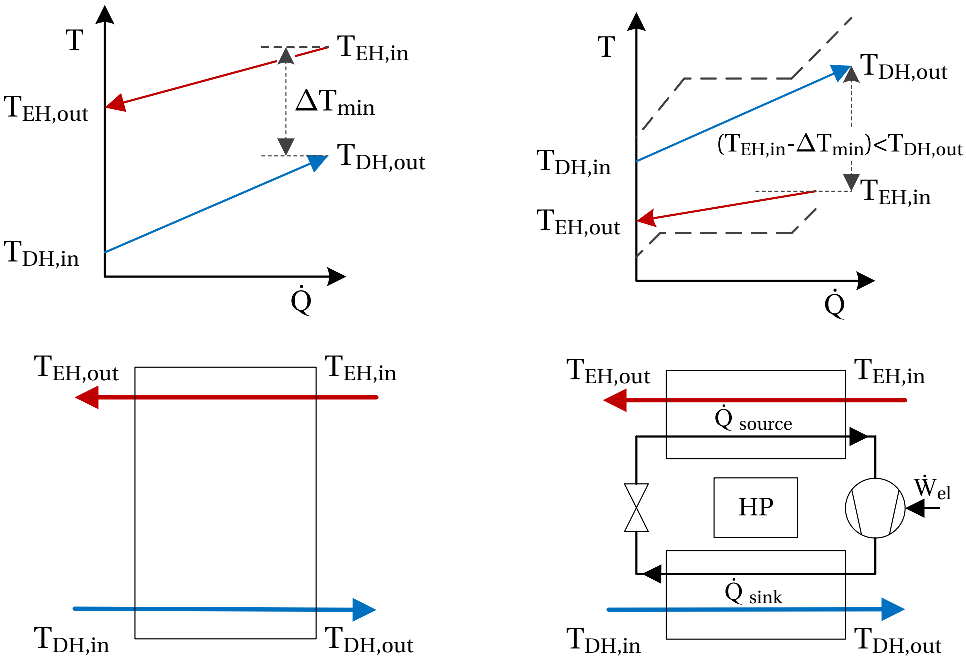
Alves and Towler [35] applies the method of pinch analysis to refineries where the assessment of hydrogen resources is necessary. The method was extended by Hallale and Liu [36] to account also for pressure losses and is called hydrogen pinch. Zhelev and Ntlhakana [37] applied the pinch method to waste water treatment from a standpoint of energy efficiency by improving the biotechnological process integration. This requires the improvement of the oxygen utilisation and the actual biodegradation process. The approach is to use the oxygen supply targeting in a substrate and the dilution rate.

2.4 Heat recovery

The feasibility and optimal technical configuration for the utilisation of the excess heat or heat exchange between process streams depends on several factors. The temperatures of the heat source (e.g. excess heat) and source (e.g. district heating) and the minimum temperature differences in the heat exchanger play an important role. Two possibilities for the heat recovery are shown in Figure 2.3 and two combinations of those in Figure 2.4. The example of using excess heat for district heating is used in the following to present the concepts.

A direct utilisation of the heat source is possible when the excess heat temperature, $T_{\mathrm{EH,in}}$, is by the minimum temperature difference ΔT_{min}, higher than the required supply temperature of the district heat, $T_{\mathrm{DH,out}}$. The excess heat stream is also of a higher capacity, which was assumed to be always the case as the district heat capacity was seen as a variable. This case is shown in Figure 2.3a.

The second case is shown in Figure 2.3b where a heat pump is required to lift the temperature of the heat source. This is required when the temperature of the excess heat, $T_{\mathrm{EH,in}}$, after the subtraction of the minimum temperature ΔT_{min}, was below the required supply temperature, $T_{\mathrm{DH,out}}$.



(a) Direct

(b) Heat pump

Figure 2.3: Overview of the configuration and TQ diagram of the possible excess heat recovery systems for thermal utilisation.

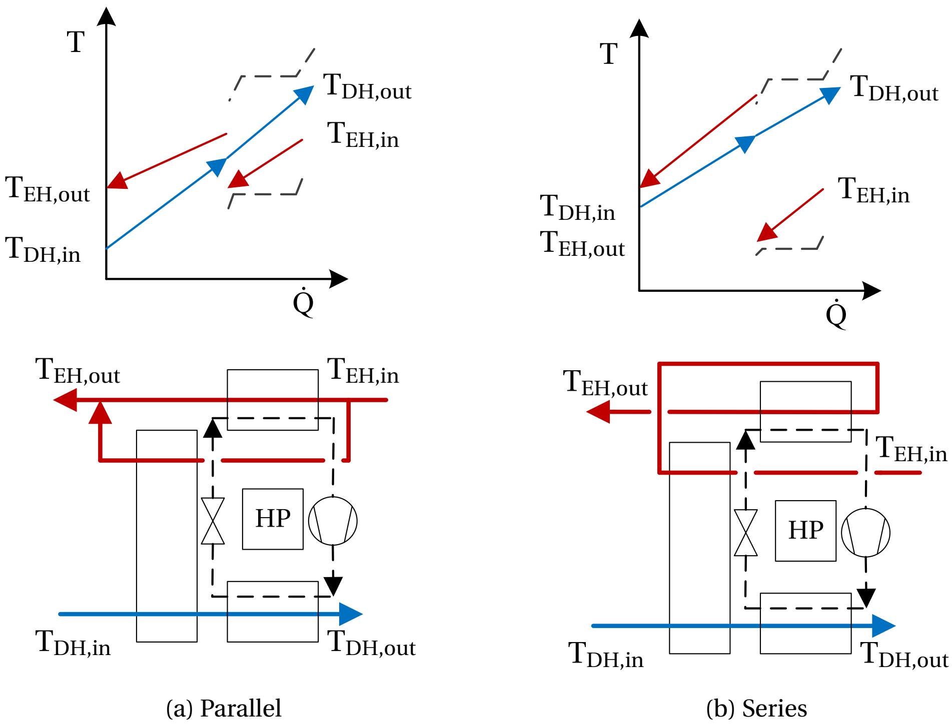


Figure 2.4: Overview of the configuration and TQ diagram of the possible excess heat recovery systems for thermal utilisation using a combination of direct heat transfer and heat pumps.

If the second case is true, but the temperature of the excess heat, $T_{\mathrm{EH,in}}$, is by more than ΔT_{min} higher than the inlet temperature of the sink, $T_{\mathrm{DH,in}}$, a solution shown in Figure 2.4a would be possible. A combination of a direct heat exchange and a heat pump, as shown in Figure 2.4a, can be used to preheat the sink inlet temperature in the heat pump [38, 39]. The resulting smaller temperature lift in the heat pump increases the overall system performance. It is necessary to find the optimal configuration and size of the equipment to fulfil heating or cooling targets.

A fourth case is possible when the excess heat temperature, $T_{\mathrm{EH,in}}$, is by more than ΔT_{min} higher than the inlet temperature of the sink, $T_{\mathrm{DH,in}}$, and the excess heat can be cooled down below the sink inlet temperature. As shown in Figure 2.4b, the sink is first preheated with a direct heat exchange and is then boosted with a heat pump to the required outlet temperature. In contrary to Figure 2.4a, the direct heat exchange is in series with the heat pump.

The effectiveness of heat pumps is described with the Coefficient of Performance (COP). The COP denotes the ratio of useful heat, $\dot{Q}_{\mathrm{sink}}$, to the amount of electric energy added to the heat pump, $\dot{W}_{\mathrm{el}}$, as shown in Eq. 2.5. The difference of the useful heat and the work added is the heat supplied from the source.

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{sink}}}{\dot{W}_{\mathrm{el}}} \tag{2.5}$$

The maximum obtainable COP, which can be reached by a heat pump, is found by using either the Carnot or Lorenz cycle. The Carnot approach assumes that the heat transfers take place at a fixed temperature. The Lorenz approach assumes that there is a temperature glide on the sink and source side, which is the case for transcritical CO_2 heat pumps.

The real COP which is obtainable in practice can be estimated using the Carnot COP, $\mathrm{COP}_{\mathrm{carnot}}$, which is corrected with the heat pump efficiency, $\eta_{\mathrm{HP,carnot}}$. This efficiency accounts for the losses which stop the heat from reaching the theoretical maximum.

$$\mathrm{COP}_{\mathrm{carnot}} = \frac{T_{\mathrm{DH,out}} + \Delta T_{\mathrm{min}}}{\left(T_{\mathrm{DH,out}} + \Delta T_{\mathrm{min}}\right) - \left(T_{\mathrm{EH,in}} - \Delta T_{\mathrm{min}}\right)} \tag{2.6}$$

$$\mathrm{COP}_{\mathrm{real,1}} = \eta_{\mathrm{HP,carnot}}\,\mathrm{COP}_{\mathrm{carnot}} \tag{2.7}$$

The heat pump can alternatively be modelled using the Lorenz cycle and is corrected by the Lorenz efficiency $\eta_{\mathrm{HP,lorenz}}$ to obtain the real Coefficient of Performance COP as shown in Eq. 2.8. The Lorenz COP is calculated by the thermodynamic average temperatures of the sink and source stream, which can be approximated by the logarithmic mean temperatures for streams of constant capacities. The logarithmic mean temperatures, $\bar{T}_{\mathrm{lm}}$, of the heat source and heat sink were found with Eq. 2.9 and Eq. 2.10.

$$\mathrm{COP}_{\mathrm{real,2}} = \eta_{\mathrm{HP,lorenz}}\,\mathrm{COP}_{\mathrm{lorenz}} = \eta_{\mathrm{HP,lorenz}} \left(\frac{\bar{T}_{\mathrm{lm,sink}}}{\bar{T}_{\mathrm{lm,sink}} - \bar{T}_{\mathrm{lm,source}}} \right) \tag{2.8}$$

$$\bar{T}_{\mathrm{lm,sink}} = \frac{\left(T_{\mathrm{DH,out}} + \Delta T_{\mathrm{min,DH}}\right) - \left(T_{\mathrm{DH,in}} + \Delta T_{\mathrm{min,DH}}\right)}{\ln(T_{\mathrm{DH,out}} + \Delta T_{\mathrm{min,DH}}) - \ln(T_{\mathrm{DH,in}} + \Delta T_{\mathrm{min,DH}})} \tag{2.9}$$

$$\bar{T}_{\mathrm{lm,source}} = \frac{\left(T_{\mathrm{EH,in}} - \Delta T_{\mathrm{min,EH}}\right) - \left(T_{\mathrm{EH,out}} - \Delta T_{\mathrm{min,EH}}\right)}{\ln(T_{\mathrm{EH,in}} - \Delta T_{\mathrm{min,EH}}) - \ln(T_{\mathrm{EH,out}} - \Delta T_{\mathrm{min,EH}})} \tag{2.10}$$

In this work, both the Lorenz and Carnot efficiency were used to estimate the obtainable performance of a heat pump. The Lorenz efficiency accounts for the temperature glides and makes it more accurate than the Carnot efficiency, but requires more temperatures to be fixed.

2.5 Exergy analysis

The range of application for exergy analysis is wide [40]. A large number of analyses have been conducted for power cycles, refrigeration systems and their components. Heat exchangers can be optimised by minimising the rate of entropy generation [21] and exergy based methods are used to optimise heat exchanger networks [41]. Also industrial production systems are studied and improved using exergy [42]. Other analyses used exergy to describe the efficiency of sectors or regions [43].

This section gives a brief introduction to the implications of the Second Law of Thermodynamics, followed by the exergy method. Other extended exergy methods are introduced afterwards focusing on the advanced exergy analysis.

2.5.1 Second Law methods

A central concept of the Second Law of Thermodynamics is entropy. Entropy describes the irreversibility of a system. The entropy of an isolated system will continue to increase, because of irreversible processes. The maximum possible value is reached when the closed system reaches a state of thermodynamic equilibrium [20]. When heat is transferred into a system, the state of disorder is increased, if heat is transferred from the system it will be decreased. The reversible heat transfer is described by the amount of energy transferred and the temperature at which the heat transfer in or out of the system occurs.

The second law describes the difference in the quality of different forms of energy and shows why some of the processes can spontaneously occur. The energy analysis does not take the thermodynamic quality into account and is only able to estimate energy or heat losses. By using methods which are also based on the Second Law of Thermodynamics, it is possible to get information about the optimal conversion of energy, meaning how much useful work can be obtained from heat or internal energy [44]. While some of the following Second Law Analyses are solely based on the Second Law (i.e. entropy), the exergy-based ones take also properties from the First Law of Thermodynamics into account. Rosen [45] names five approaches to Second Law Analysis

(i) Entropy analysis includes the inputs, outputs and accumulation of entropy generation.

(ii) Negentropy analysis is the opposite of entropy. Here negentropy is consumed.

(iii) Exergy consumption analysis only considers general work potentials of the system.

(iv) Physical exergy analysis does not include chemical exergy and can be used for systems where stream compositions do not change, e.g. heat exchanger.

(v) Exergy analysis includes all inputs, outputs and exergy consumption.

The complexity of the approaches increases, as more properties of the reference state have to be considered. For an entropy analysis no reference is required and for the exergy analysis the temperature, pressure and chemical composition have to be included.

2.5.2 Exergy

The exergy of a system can be defined as the maximum work that can be performed by a system when it is brought into equilibrium with its reference environment. Exergy is thus only conserved when all processes occurring in the system are reversible. Furthermore, the reference environment has to be defined, which donates the basis for the value of the exergy. The concept and theory of exergy analyses were presented and discussed in other works in detail [20, 21, 46, 47]. A summary of the main concepts is given in the following.

Exergy is always assessed with respect to an environmental state (or restricted dead state), thus this state has to be defined. As soon as the analysed system has a different temperature, pressure, chemical potential, altitude, etc. than the environmental state, the possibility to perform work exists. There are different approaches to the dead state, one being a state close to the natural environment.

The total exergy E of a system can be divided into four components, namely physical E^{PH}, kinetic E^{KN}, potential E^{PT} and chemical exergy E^{CH}, when neglecting nuclear, magnetic, electrical and surface tensions effects. The exergy content of a system can then be written as in Eq. 2.11.

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \tag{2.11}$$

The kinetic and potential energies can be theoretically fully converted to work when brought to the environmental state and their exergy content is therefore equal to their energy content. The physical exergy for a closed system is defined as in Eq. 2.12, where U, S and V are the internal energy, entropy and volume of the specified system and the subscript 0 gives the same properties at the dead state.

$$E^{PH} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) \tag{2.12}$$

The physical exergy represent the maximum amount of work that can be performed by a system as its pressure and temperature are put in equilibrium with the pressure and temperature of the reference state.

Exergy accounting

Unlike energy, exergy can be destroyed and accounts for the use of additional primary energy induced by the systems' imperfections. The exergy destruction is defined as the difference between the exergy inflowing and outflowing the system under study, and can thus be derived from the previous relations as:

$$\sum_{\text{in}} \dot{E}_{\text{in}} - \sum_{\text{out}} \dot{E}_{\text{out}} + \sum_{k} \dot{E}_k^Q - \dot{E}^W = \dot{E}_D \tag{2.13}$$

$$\sum_{\text{in}} \dot{m}_{\text{in}} e_{\text{in}} - \sum_{\text{out}} \dot{m}_{\text{out}} e_{\text{out}} + \sum_{k} \dot{E}_k^Q - \dot{E}^W = \dot{E}_D \tag{2.14}$$

where $\dot{E}$ denotes the exergy associated with a stream of matter, heat or work; e the specific exergy of a material stream; $\dot{E}_k^Q$ and $\dot{E}^W$ the heat and work exergy rates exchanged with the surroundings; $\dot{E}_d$ the destroyed exergy. The exergy losses $\dot{E}_L$ are included in the exergy stream out of the system.

Flow exergy

The specific exergy of a flowing stream of matter consist of physical, chemical, kinetic and potential components. Excluding the kinetic and potential components, the specific exergy can be expressed as follows:

$$e = [(h - h_0) - T_0 (s - s_0)] + \left[\sum_{j} \left(\mu_{j,0} - \mu_{j,00} \right) x_j \right] \tag{2.15}$$

The first term of Eq. 2.15 describes the physical exergy, which is the maximum useful work that can be extracted from the stream when brought to environmental conditions (temperature and pressure). The second part, the chemical exergy, is the maximum available work that can be extracted from the stream when brought from the environmental state (denoted with the subscript 0) to the dead state (denoted with the subscript 00).

Chemical exergy

The chemical exergy is, according to [20, p.32], equal to the maximum amount of work that can be obtained when a substance is brought from the restricted state to the dead state by a process including heat transfer, mixing/ separation, chemical reactions and exchange of substances only with the reference environment. The maximum work is attained when the process is reversible. Alternatively, chemical exergy can also be viewed as the exergy of a substance that is at the reference-environment state.

Chemical exergy is important for many exergy applications, e.g. combustion, phase change and chemical reactions. The literature discusses chemical exergy in detail and exergy contents for the most common fuels can be found there as well [21].

In this work only the chemical exergy for the fuels and combustion gasses were used. These were calculated based on the chemical fuel composition in Denmark [48], where applicable. For liquid and solid fuels, the approach by Szargut [49] and for gaseous fuels by Bejan et al. [21] was used. The ratio of the specific chemical exergy e^{ch} to the lower heating value (LHV) of the fuel, Φ, is given for the different fuels in Table 2.1 and can be calculated with Eq. 2.17.

The chemical exergy per mole of gas mixture can be found with Eq. 2.16, where $\bar{e}_k^{CH}$ is the standard chemical exergy [49] for the gas k, $\bar{x}$ the mole fraction and $\bar{R}$ the universal gas constant.

$$e^{\mathrm{ch}} = \sum \bar{x}_k \bar{e}_k^{CH} + \bar{R} T_0 \sum \bar{x}_k \ln \bar{x}_k \tag{2.16}$$

$$e^{\mathrm{ch}} = \phi_{\mathrm{f}} \, \mathrm{LHV} \tag{2.17}$$

Table 2.1: Properties of fuels used in this work at reference conditions with the *LHV*

Fuel	LHV [MJ kg^{-1}]	ϕ [-]	e^{ch} [MJ kg^{-1}]
Refinery Gas	52.0	1.161	60.4
LPG	46.0	1.056	48.6
Gasoline	43.8	1.071	46.9
Fuel Oil	42.7	1.067	45.6
Diesel	42.7	1.068	45.6
Heavy Fuel Oil	40.7	1.066	43.3
Petroleum coke	31.4	1.048	32.9
Natural Gas	48.0	1.065	51.2
Coal	24.2	1.076	26.1
Coke	29.3	1.048	30.7
Waste	10.5	1.152	12.1
Wood Chips	9.3	1.193	11.1
Wood Pellets	17.5	1.072	18.8
Straw	14.9	1.084	16.2
Biogas	19.8	1.041	33.7
Bio Oil	36.7	1.114	40.9

Exergy of work and heat

The exergy, $\dot{E}^W$, associated with work is equal to its energy $\dot{W}$, whilst the exergy transferred with heat $\dot{E}_k^Q$ at the temperature T_k depends on the heat transfer and dead state temperatures (in this case, above ambient conditions).

$$\dot{E}^W = \dot{W} \tag{2.18}$$

$$\dot{E}_k^Q = \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k \tag{2.19}$$

Dead state

The dead state conditions are selected as a temperature of 15 °C, a pressure of 1.013 bar, and with the reference chemical environment of Szargut [49]. The environmental temperature is taken as the average conditions in Denmark. It has an impact on the calculations of the chemical energy and exergy of fuels, which can vary in a range of +/- 0.5 % per 10 °C change for the fuels investigated in this study [50]. A varying dead state temperature in the range of 0 °C to 25 °C showed no significant impact on exergy efficiencies in a sectorial analysis [51].

Exergy efficiency

Exergy analysis is often used to establish the performance of a system, for which several indicators can be used. Commonly the exergy destruction ratios, exergy loss ratios and exergy efficiencies are found [21]. In the first step an Exergy balance over a control volume is created as shown in Eq. 2.20, where the sum of the exergy flow out of the control volume $\dot{E}_e$ and the exergy destruction is equal to the exergy flow into the control volume $\dot{E}_i$.

$$\dot{E}_{in} = \dot{E}_{out} + \dot{E}_D \tag{2.20}$$

Some of the exergy lows out of the control volume will be losses and referred to as $\dot{E}_L$. In order to identify the exergy efficiency it is necessary to define a product and a fuel of the thermodynamic system under investigation. The exergy product is the desired effect of a system or component, e.g. heating of a stream of matter or work output of a turbine. The exergy fuel is the required input. The exergy balance can then be formulated as shown in Eq. 2.21, where $\dot{E}_F$ and $\dot{E}_P$ are the supplied fuel and product. The exergy efficiency is then found using Eq. 2.22

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \tag{2.21}$$

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} \tag{2.22}$$

Another performance indicator is the exergy destruction ratio y_D^* of a component (Eq. 2.23).

$$y_D^* = \frac{\dot{E}_D}{\dot{E}_{D,tot}} \tag{2.23}$$

It has to be noted that relying solely on exergy analysis for the assessment of some systems can result in misleading conclusions. As stated before, exergy refers to the maximum useful work which can be obtained from a system when it is brought into equilibrium with the environment. In some systems, e.g. combined heat and power plants, where also heat is an output and leads to a desirable higher fuel utilisation, exergy efficiency does not reflect that trend as clearly as energy efficiency [52]. Exergy analysis should thus be one of multiple methods, based on energy and environmental indicators, to evaluate these systems [44].

2.5.3 Advanced exergy analysis

When applying a conventional exergy analysis to thermal systems it is not possible to determine the real potential for optimisation and the mutual interdependencies of the components in the system [53]. A conventional exergy analysis highlights the defects and irreversibilities of the system and process, but does not show which ones can be reduced in practice. For example, a simple gas-turbine cycle is characterised by a high exergy destruction in the combustion chamber, but few improvements are possible. By using advanced exergy analyses the avoidable exergy destruction and the exergy destruction caused by the component itself can be found. In the gas-turbine cycle it would be possible to identify this unavoidable exergy destruction in the combustion chamber. The exergy destruction is, in advanced analyses, divided into endogenous and exogenous parts and in unavoidable and avoidable exergy destruction. This can give a better understanding of the system and its optimisation potential.
Unavoidable and avoidable exergy destruction takes into account that some of the exergy destruction can not be prevented due to physical and economic constraints [54]. This could be for example the maximum efficiency of a turbine. The optimisation of the system should thus focus on the avoidable part of the exergy destruction [55]. The rate of exergy destruction is divided in to two parts for the component k, the avoidable part $\dot{E}_{D,k}^{AV}$ and the unavoidable one $\dot{E}_{D,k}^{UN}$.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{AV} + \dot{E}_{D,k}^{UN} \tag{2.24}$$

Exogenous and endogenous exergy destruction is analogous split into two parts. Here the endogenous part $\dot{E}_{D,k}^{EN}$ of component k is associated solely with the irreversibilities occurring within it, when the remaining components operate in an ideal way and the component being considered operates with its current efficiency [56]. The exogenous part of the exergy destruction $\dot{E}^{EX}_{D,k}$ within component k is caused by the irreversibilities that occur in the other components.

$$\dot{E}_{D,k} = \dot{E}^{EN}_{D,k} + \dot{E}^{EX}_{D,k} \tag{2.25}$$

These two exergy destructions can be further combined into avoidable and unavoidable endogenous and exogenous exergy destruction.
In the literature the application of advanced exergy analyses is focused so far on absorption [56] and vapor-compression refrigeration machine [57], gas-turbine power cycles [57], combined cycle power plants [53] and industrial systems for rubber production [58]

Conducting an advanced exergy analysis of such systems gives a more detailed insight into the causes of exergy destruction and therefore can give a better approach for the optimisation. This is particularly useful when a part of the exergy destruction results from the interactions with other components. Furthermore it is possible to receive a more practical value for the avoidable exergy destruction. However the complexity of the calculations is considerably increased, introducing four new values in the combined analysis. Furthermore assumptions or data for the theoretical and unavoidable conditions have to be determined. The conditions chosen in this work are presented in Chapter 7, where an advanced exergy analysis of a milk powder factory was conducted.

These advanced methods can also be extended to include the exergonomic and exergoenvironmental concepts [55, 59] as described amongst others in the following section.

2.5.4 Other exergy methods

The application area and the method of exergy has been continuously refined and extended by many authors. In the following a brief overview of selected methods is given which are important to this work.

Exergoeconomics Tsatsaronis and Morosuk [60] defined exergoeconomics (or thermoeconomics) as an exergy-based method that identifies and calculates the location, magnitude, and causes of costs in an energy conversion system. An exergoeconomic analysis can be conducted at a component level of a system. Such an analysis will reveal the relative cost importance of each component and will provide suggestions for improving the overall cost effectiveness of the system. The objectives of an exergoeconomic analysis can be summarised as [21]

- to calculate separately the costs of each product generated by a system having more than one component

- to understand the cost formation process and the flow of costs in the system
- to optimize specific variables in a single component
- to optimize the overall system

The fundamentals of exergoeconomics and the methods are explained in detail in [21, ch. 8], [47, ch. 2.5] and [20, ch. 20].

Exergoenvironmental analysis Similar to an exergoeconomic analysis, the exergoenvironmental analysis identifies and calculates the location, magnitude, and causes of environmental impact in an energy conversion system [61]. As the exergoeconomic analysis is conducted at the component level and reveals the environmental impact of a component associated with the overall system. In an exergoenvironmental analysis, the values of a one-dimensional characterization indicator are obtained performing a life cycle assessment (LCA) [60].

Cumulative exergy consumption Cumulative exergy consumption (CEC) was first introduced by Szargut and Morris [62]. The idea behind CEC is the additive nature of exergy. When a production chain is seen as a series of elemental processes, each one will add some exergy to its inputs, destroy some exergy in its internal irreversibilities, and deliver a product with some added exergy value. The final product has therefore a Cumulative Exergy Content that can be exactly computed once the production process is known. For each commodity that we use in our society, including dematerialized ones like power and electricity a CEC can be given [40]. This method was applied to several processes and systems, for instance to the industrial chlor-alkali process [63] and multiproduct separation processes [64].

Other The CEC method was expanded to the extended exergy accounting (EEA) method, by additional exergy flows that represent the exergy equivalents of the capital, labour and environmentalremediation Production Factors [40, 65]. The method of exergy life cycle assessment [20] builds on a LCA. The exergy destruction in a system is one of the indicators of its environmental impact as it describes the efficiency at which energy resource are conserved. The inclusion of exergy analyses in all stages of the system evaluation can thus give useful insights. The renewability exergy index takes into account the exergy associated to the fossil fuels required, the destroyed exergy, the needed exergy to deactivate the wastes, the exergy of by-products and untreated waste [47, p.51].

2.6 Economic analysis

Economic analyses are performed on different levels throughout this work. The economic costs for specific technical solutions are evaluated, as well as cost estimations on a system level without any technical details are made. Different approaches are selected, which are explained in the corresponding chapters. Some economic concepts, which are universally applicable and applied in this work are stated in the following.

If not stated otherwise, the investment costs I refer to the total capital investment costs, which is the sum of the direct, indirect and other costs [21]. If the direct costs were found for a different year than the reference one, the chemical engineering cost plant index (CEPCI) was used. The CEPCI is applied to the known costs C in the year a to obtain the costs in year b as shown in Eq. 2.26.

$$C_{\mathrm{b}} = C_{\mathrm{a}} \frac{\mathrm{CEPCI_b}}{\mathrm{CEPCI_a}} \tag{2.26}$$

The cash flow, CF, for each year n was found using Eq. 2.27, where the difference between revenue R and expenditure E is multiplied is corrected by inflation, i_{infl}.

$$\mathrm{CF}_n = \left(1 + i_{\mathrm{infl},n}\right)\left(R_n - E_n\right) \tag{2.27}$$

The capital recovery factor, CRF, is used to annuitise the investment costs over the lifetime, N_L, and is found using the interest rate, i, as shown in Eq. 2.28. The lifetime, N_L, for the investment costs is not necessary the same as the lifetime, N, for the economic analysis. There might be stricter requirements for the recovery of the investment costs, which would be expressed in N_L being less than N.

$$\mathrm{CRF} = \frac{i\,(1+i)^{N_L}}{(1+i)^{N_L} - 1} \tag{2.28}$$

To assess a given investment several economic indicators were used. The net present value (NPV) is found following Eq. 2.29 as the sum of all CF discounted with the discount rate d of the project as well as the discrete and continuous cash flows in the entire life-cycle of the project [66]. The NPV is an absolute measure and is most useful when comparing different investment options. A positive sign of the NPV indicates however that the project is profitable over the lifetime.

$$\mathrm{NPV} = -\left(\sum_{n=1}^{N_L} (\mathrm{CRF_n} \cdot I)\right) + \sum_{n=1}^{N} \left(\frac{\mathrm{CF}_n}{(1+d)^n}\right) \tag{2.29}$$

The internal rate of return (IRR) is found by setting the NPV to zero and solving Eq. 2.30 for

IRR. The IRR is a relative measure expressing the profitability of the investment.

$$0 = \mathrm{NPV} = -\left(\sum_{n=1}^{N_L} (\mathrm{CRF_n} \cdot I)\right) + \sum_{n=1}^{N} \left(\frac{\mathrm{CF}_n}{(1+\mathrm{IRR})^n}\right) \tag{2.30}$$

The simple payback time (SPT) in Eq. 2.31 is found by dividing the investment costs through the mean annual cash flow CF.

$$\mathrm{SPT} = \frac{\sum_{n=1}^{N_L} (\mathrm{CRF_n} \cdot I)}{\sum_{n=1}^{N} (\mathrm{CF}_n) \cdot N^{-1}} \tag{2.31}$$

The unit costs of heat delivered c_H, is found as the sum of transactions divided by the heat delivered within the lifetime.

$$c_H = \frac{I + \sum_{n=1}^{N} \mathrm{CF}_n}{Q \cdot N} \tag{2.32}$$

The selected values for the economic analysis, as well as the boundary conditions and costs are presented in Chapter 5, 6 and 10, where economic analyses were performed.

2.7 Uncertainty and sensitivity analysis

Numerical models can most of the time not be validated, in the sense that they are proven to be true [67]. It is more correct to describe a model as being extensively verified, by having tested the model, for instance to its internal consistency or relative to the model's ability to explain the outcome in a convincing way. The uncertainty in the prediction of a model can arise from three sources [68], namely simulation variability (stochastic variability), input uncertainty (incomplete knowledge of input values) and structural uncertainty (assumptions used in mathematical form or structure). Uncertainty analysis quantifies the uncertainty of the model output, while sensitivity analysis investigates the proportion of uncertainty that can be attributed to the different model inputs [67]. The uncertainties should be taken into account when assessing the model output and the impact of the parameters on the model output should be analysed, in order to correctly interpret the results and draw conclusions. In this work the input uncertainty and importance of parameters were assessed for some of the developed models (Chapter 6 and 10). The applied methods are introduced in the following.

2.7.1 Uncertainty analysis

To quantify the uncertainty of (complex) numerical models several methods exist, such as Bayesian analysis in combination with evolutionary optimization, differential analysis, response surface methodology and Monte Carlo (MC) analysis [69, 70]. In this work the MC method, a sampling based approach to uncertainty, was used. This method is engineering standard and generally accepted as being efficient in computational times and reliable [68]. The MC method was developed by Metropolis and Ulam [71] finds the probability of the model output, considering the uncertain inputs. With the MC method the model is evaluated a number of times N, using random input values generated within the input uncertainty space. The work flow of this analysis consists of four steps and was described by Sin and Gernaey [72].

1. Input uncertainty definition
2. Sampling from the input space
3. Perform Monte Carlo simulations
4. Evaluate and analyse the results

The definition of the input uncertainty is described as the most crucial step, as it will determine the reliability of the outcome of the analysis. In this work the uncertain inputs were described using four types of probability distributions, namely normal (N), half-normal (HN), uniform (U) and gamma (G). The distribution are visualised in Figure 2.5. For each uncertain input parameter an assessment of the distribution was made based on own and expert assessments, as well as literature data.

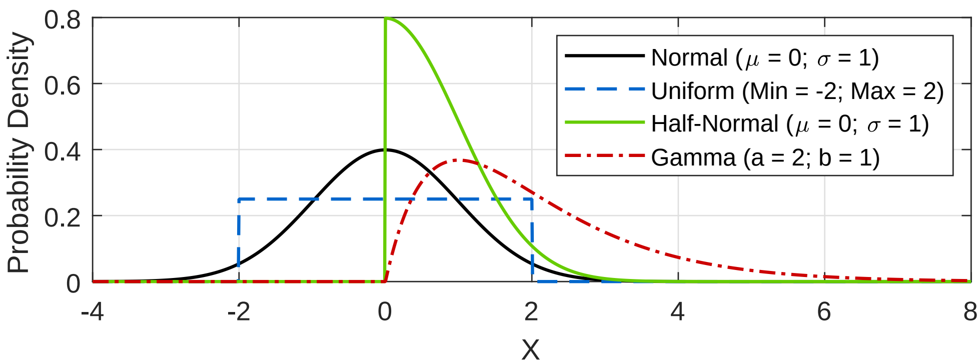
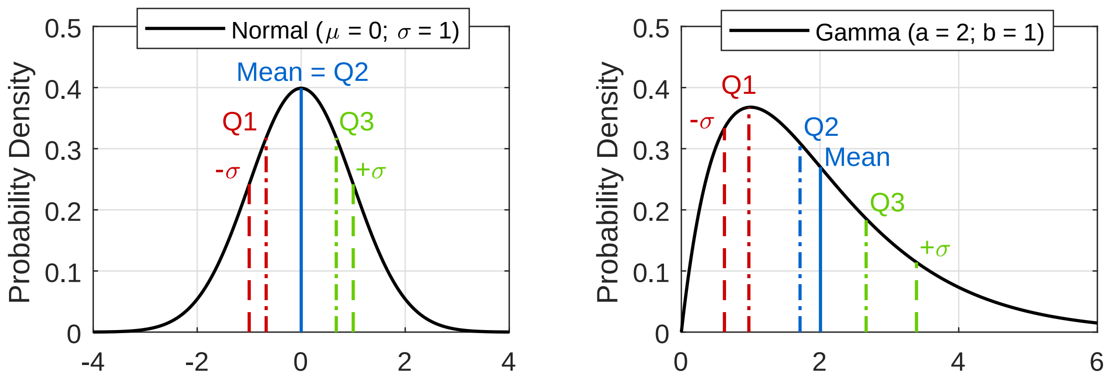


Figure 2.5: Probability density function of distributions used in this work.

The second step, the sampling within the input space was done using the Latin hypercube sampling (LHS). LHS is an accepted method which can produce more stable results than for instance random sampling [73]. Simple random sampling can have certain monotonicity conditions and LHS appears to be a good method to use for selecting values of input variables [74]. The samples of the input space, created with the Matlab function *lhsdesign* are then translated into the real model values [75].

With the real model values, the model function is executed N times (MC simulations as the third step) and the output matrix is evaluated (fourth step). In this work the mean, standard deviation and the quartiles of the distribution are reported. An example of this values are shown in Figure 2.6a for a normal distribution and in Figure 2.6b distribution. The reported values were chosen to best describe the distribution of the model output vector. Either the mean and standard deviation are given or the second quartile, Q2, which is equal to the median value, together with the first and third quartiles.



(a) Normal distribution (b) Gamma Distribution

Figure 2.6: Probability density function of distributions used in this work.

2.7.2 Sensitivity analysis

The sensitivity analysis (SA) of a model output is an important element in the model building and interpretation process [76]. Good models can be used amongst others to analyse "what if" questions, as part of a sensitivity analysis, allowing to highlight aspects of the investigated system which need further studying or where empirical data is needed [77]. There are several established methods to perform sensitivity analyses, which have each their merits and application areas [67, 76]. In this work three methods are applied. They are used gain a better understanding of the developed numerical models, the influence of different parameters on the model output and for the validation of the model. Local sensitivity methods analyse how a small perturbation in the parameter input impacts the model output. On the other hand, global sensitivity methods look at the variance of the model output and how it is influenced by the input variability. The first two methods are local, while the third one based on the Monte Carlo simulations is global.

One-factor-at-a-time

The simplest form of a sensitivity analysis might be a parameter analysis, also called one-factor-at-a-time (OAT) analysis. This method is in practice frequently applied. The value of the parameters is modified one at a time and the effect of the change of the input parameter on the model output is recorded. The impact on the results can then be graphically analysed.

This approach does not require any detailed knowledge of statistics or further treatment of the recorded model output. It is however difficult to quantify the impact one parameter has on the model output. Furthermore this method becomes inefficient if many parameters are to be analysed. Other, more advanced and systematic, sensitivity methods build however on OAT analyses.

Morris screening

The method of Morris [78] is an effective and easy to implement tool, which allows to detect a few important input parameters amongst a large set of inputs to the model [79, 80]. This method estimates the elementary effects (EE) for all uncertain parameters of the model on the model output [70]. Morris screening is a very computational efficient method and follows this general approach: first samples are created using the Morris sampling, followed by the model evaluations. The EE are then determined for each input and the input parameters are ranked according to their mean and standard deviations. Guidelines on the use of Morris Screening can be further found in [79], along with a description of using normal distributed parameter uncertainties. When using the Morris sampling each parameters is sampled at a specified number of selected values, called levels. The distance between two consecutive levels is called the perturbation factor Δ. In the resulting input space, samples are calculated and the procedure is repeated a number of times, r. Based on the selection, only $r \cdot (k+1)$ model evaluations are required. The Morris Screening has thus three degrees of freedom, which have to be chosen by the user: the number of levels p, the number of repetitions r and perturbation factor Δ. Typical values for p are 4, 6 and 8 and r is in the range of 4 to 15. However, the optimal setting can be out of this typical range [81].

The EE is calculated for each input parameter X_j and model output Y calculated using Eq. 2.33. Where the first part of the sum in the numerator is model output corresponding to a Δ change in X_j and the second part the model output at the initial input parameter [70, 80].

$$EE^i_{X_j} = \frac{Y\left(X^i_1, X^i_2, X^i_j + \Delta, ..., X^i_N\right) - Y\left(X^i_1, X^i_2, X^i_j, ..., X^i_N\right)}{\Delta} \tag{2.33}$$

As the EE are local measures, they are calculated at random points in the input space to approximate the distribution of the EE. The mean and standard deviations of these distributions are then used to assess the sensitivity. Type II errors occur when an important factor on the model output is not identified. These errors can be avoided by comparing the estimated mean of the distribution for the absolute values of the elementary effects [67]. This is done by using the absolute mean of the distribution μ^*.

Standardised regression coefficient

To obtain the standardised regression coefficient (SRC), as a sensitivity indicator, a linear regression model for the output function is created [67, 76, 82]. The SRC's are then calculated based on the least square regression of the performed Monte Carlo simulations. Scatter plots can be used to visually analyse the model behaviour of the parameters. The regression coefficient b_i of the input variable i, can be found for a model output vector Y of the size N for the simulation number j as follows in Eq. 2.34. Here, k represents the number of variables and ϵ the error term.

$$Y_j = b_0 + \sum_{i=1}^{k} b_i X_j^i + \epsilon_j \tag{2.34}$$

The SRC's are then computed with Eq. 2.35 from the regression coefficients and the respective standard deviations of the sample averages of the output Y and the input parameter X_i.

$$SRC\left(Y, X^i\right) = b_i \frac{\sigma_{X^i}}{\sigma_Y} \tag{2.35}$$

The SRC can take a value between [-1,1] for each parameter, describing the magnitude of the influence and if it has a positive or negative influence. The sum of the squared SRC is equal to one. Applying this method, the R^2 (percentage of data variance) allows a direct verification of the effectiveness of the regression model. A low value of R^2 would mean a poor regression and thus the inability to assess the influence of the input variables based on the SRC [76]. Values above 0.7 mean that the model could be sufficiently linearised [70].

3 Energy and exergy analysis of the industry

In this chapter a detailed analysis of the Danish industry and the applied methods is presented. The analysis has a focus on evaluating and describing the energy use, conversion efficiencies and potential for recovery. The methods that were further developed, in particular with respect to exergy analysis and system efficiencies are described in more detail.

3.1 Introduction

The analysis of the energy use and conversion in the industrial sector of a country or region can have many motivations. Such an analysis can be used as the basis to determine energy saving potentials [83, 84], barriers to energy savings [85], historical trends in energy use [8], potentials for creating load flexibility and changing energy carriers [86]. The methods to establish such an analysis can be very different and their selection depends, amongst other factors, on the targets for accuracy, available data and scope of the study. For the classification of the methods, Brückner et al. [87] stated three dimensions that should be considered, namely the scale of the study, the method for data acquisition (survey or estimation) and the applied approach (top- down or bottom-up) to obtain the result. Surveyed data is usually based on questionnaires or official reports, while estimates rely on energy and efficiency factors. It was however noted by Brückner et al. [87], that surveys can in reality be estimated, if the data is not measured. The top-down approaches use generalised data which is broken down to find specific results. Bottom-up approaches start from single case studies (e.g. process analysis) which are aggregated to general results. A combination of these two approaches is possible, when elements of the top-down approach are complemented with case studies.

The method for a complete analysis can be based on several sequential steps, which include all industrial sectors. Fleiter et al. [83] applied a method for analysing the industry sector in Germany, which started by selecting relevant sectors. For these sectors relevant processes were chosen, for which a technical and economic analysis was performed, resulting in the current energy use patterns of the sectors and the analysis of energy saving options.

The method applied in the current and the following chapter was largely based on a top down approach complemented by case studies using both estimates and surveys. Figure 3.1 shows the overall structure and level of detail for the analysis of the industrial sector in Denmark. The energy use from the industry was broken down to a process level, for which the temperatures were estimated and partly found by case studies. The distribution of energy use to the process level was primarily based on data from Denmark Statistics [48] and Viegand Maagøe A/S [88]. The method is explained in more detail in the respective chapters, an example of industry data is however given in the following to give a better understanding of the data background.

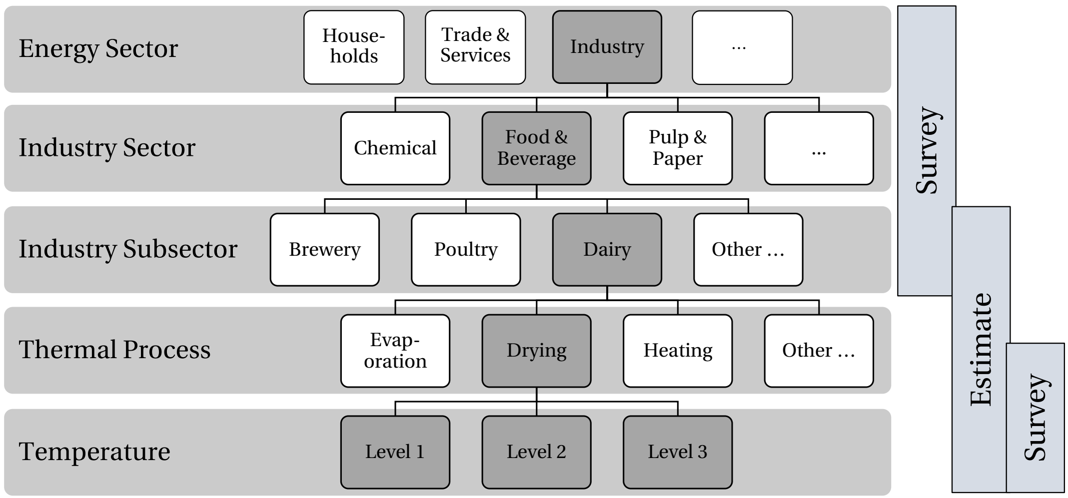


Figure 3.1: Structure of the energy model of the industrial sector with the main sources of data.

Figure 3.2 shows the final energy use in the industry by sector and energy type. It can be seen that food, oil refinery, plastic, glass and concrete industries have the highest share in energy use. They are furthermore largely dependent on fossil fuels, in particular natural gas and oil products. Many sectors, such as the food, chemical and metal ones have further a high degree of electricity use. An analysis of the industry sector should thus include the possible inefficiencies in the energy conversion processes for electricity and heat production. Following the structure from Figure 3.1, the breakdown from industry sector to industry process is shown in Figure 3.3 with the example of the manufacturing of dairy products. Dairy products are the single food sector with the highest energy use in Denmark. The total energy input to this sector can be disaggregated to the final energy use in the sector [88]. This disaggregation was obtained by process information (general or case study specific) for the most important products of the sector. In the case of dairy products the processes for cheese, milk and milk powder are used. To describe the industry sector and its subsectors the classification system of Denmark [89] was used, which is based on the statistical classification of economic activities in the European Community, abbreviated as NACE [90]. The NACE classification are the first 4 numbers in the Danish code, classifying the division (e.g. food industry), group (e.g.

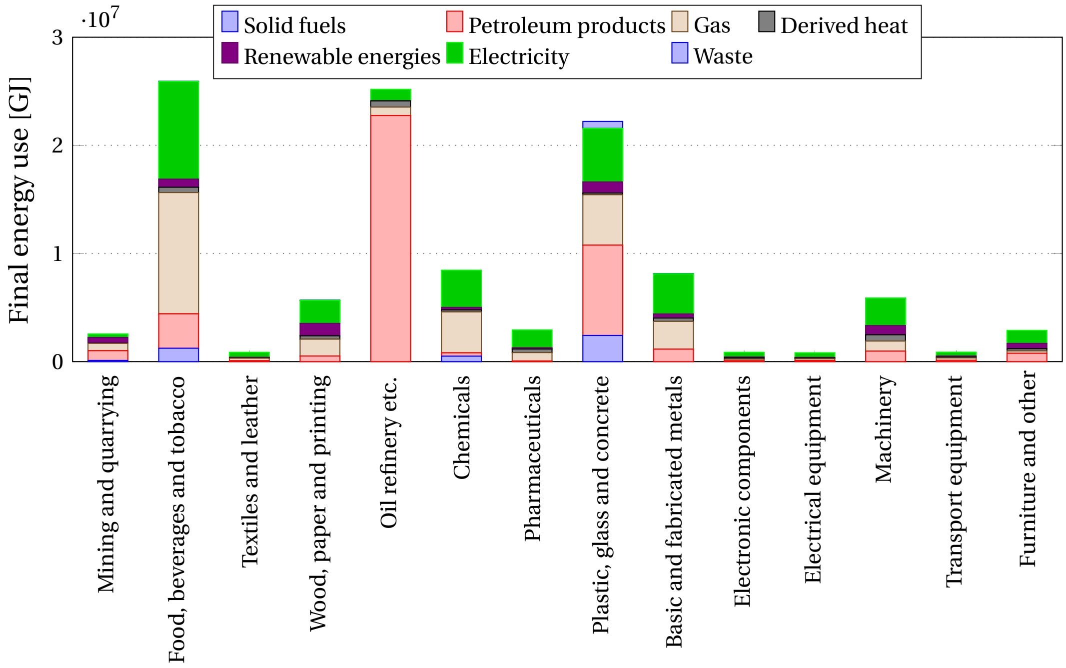


Figure 3.2: Final energy use by energy carrier and industry sector in 2015 in Denmark [48].

Processing and preserving of meat and production of meat products) and class (e.g. Processing and preserving of meat). The Danish code however has one more level called branch (e.g. Processing of pork meat). This work used in some cases branches in the analysis but also creates own groupings where necessary. This chapter is based on the article [91][P1]

3.1.1 Literature review

The application of energy-based methods is useful for tracking the energy flows within a given system. However, energy analysis has inherent limitations, as it cannot be used for assessing the performance losses within a given system. As described in Chapter 2, analyses also including the Second Law of Thermodynamics can overcome these limitations. The article by Hammond [44] presents a comparison and summary of thermodynamic methods for the analysis of industrial energy-systems. Further, Hammond and Norman [92] investigated the technically recoverable surplus heat and Ammar et al. [93] discuss low grade heat capture from the UK industry, both applying exergy methods and analysing various industries.

There has been a number of studies conducted, which analyse the energy and exergy efficiency of a country. An overview of some of the most notable ones is given in the following. An exergy analysis on a sectoral level was first conducted for the United States by Reistad [94], where also the merits of a second law analysis were pointed out. This approach was later followed by Rosen [43] for an analysis of Canada. Also following the approach of Reistad, the countries Turkey [95] and Saudi Arabia [96] were analysed, to find the efficiencies of the

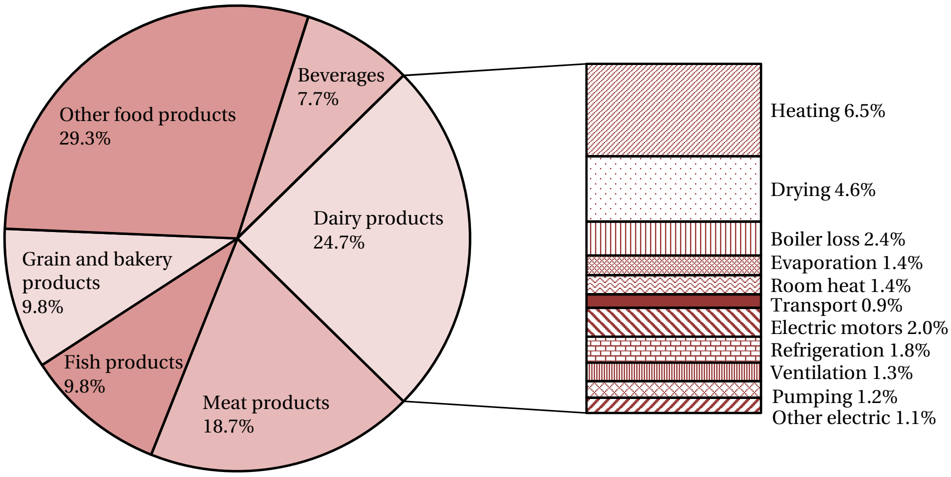


Figure 3.3: Share of the subsectors' final energy use in the food industry and break down of process energy use in the dairy industry [48, 88].

main sectors. For the United Kingdom a detailed exergy analysis of the energy system was performed by Hammond and Stapleton [97], analysing a period of 34 years and tracking structural changes of the system. The inclusion of other resources than fuels in an exergy analysis was done for the Swedish society by Wall [98]. For the case of Norway, Ertesvåg [99] applied the method of Extended Exergy Accounting, also including other flows than energy resources and accounting for example for labour and monetary fluxes. These works demonstrated the usefulness of thermodynamic methods for depicting opportunities for better energy management, and they showed significant potentials for improvements in the countries and different sectors. For Saudi Arabia an overall exergy efficiency of around 30 % was found [96] and for Turkey of 25 % [95]. For the industrial sector in the United Kingdom and an exergy potential for improvement of 1200 PJ was reported for the year 1999 [97], while in all sectors in Canada 6450 PJ of exergy was wasted in 1986 [43].

A review of the studies and methodologies was performed by Hepbasli [100] and Utlu and Hepbasli [101]. They suggested a formalisation of the methods for modelling the sectoral energy and exergy utilisation, starting from the listing of all energy and exergy inputs and outputs, then with a sub-grouping of the sectors into utility, industrial, commercial, residential & transportation, and a further splitting into each end-user.

Other works focused on specific sectors, such as Dincer et al. [102] and Liu et al. [103] on the residential sector of Saudi Arabia and China, while the one of Motasemi et al. [104] dealt with the case of the transport sector of Canada. Zhang et al. [105] used exergy to account for the national resource utilization of China and identified that the input of natural resources was the main driver for past developments with large rates of exergy destruction and loss. The studies that are the most relevant to the present work may be the ones of Al-Ghandoor et al. [106], who applied energy and exergy methods, as well as Sanaei et al. [107], Dincer et al.

[108] and Oladiran and Meyer [109], all focusing on the industrial sector of a country. They established and compared the efficiencies of several industrial sectors for the cases of the United States, Iran, Saudi Arabia and South Africa. These works, however, did not distinguish between the destroyed exergy due to irreversibilities and the exergy lost to the environment. In addition, great differences in the level of detail, e.g. the number of considered processes and the number of industries accumulated in sectors, exist amongst them.

In this work the lacks of the previous studies were addressed by increasing the level of detail and determining the excess heat temperatures of the processes. This chapter further presents the first detailed exergy analysis of the industry sector in Denmark, using energy and exergy methods. A comparison of the total site and system efficiency was added for the years 2006 and 2012. In addition, aggregated sectoral results are presented to make this work comparable to others. This analysis was built on 22 industries with up to 10 thermal and 13 electric end-use categories, and divided thermal losses into conversion and direct losses. The inefficiencies were split into their exergy destruction and losses part, based on the excess heat temperatures. This approach allowed therefore for a better quantification of the real thermodynamic recovery potential, compared to relying exclusively on the energy or exergy efficiency indicators. A more complete comparison of the industries was carried out, which was possible through the inclusion of the inefficiencies in the utility sector. The results were finally compared to the previous studies in this field, which focused only on fewer main sectors in their analyses, and the findings showed therefore the additional insights derived from a more thorough approach.

The main objectives were to (i) show where in the Danish industry the lowest efficiencies and highest losses occur, (ii) document the changes in the industrial sector over the last years, and (iii) pinpoint the industries with potential for recovering energy and exergy. As proposed and formalised by Soundararajan et al. [110], the results in exergy terms are presented in a Grassmann diagram.

3.2 Methods

3.2.1 Case study

Industrial sector

The industry sector in Denmark consists of several subsectors, without being dominated by single types of industries. The total energy input to the industry sector, excluding the extraction of oil and gas resources, agriculture and the service sector, amounted to 112 PJ in 2012, which was a reduction of 12 % compared to 2006 [48]. In this study, the 22 most energy intense industries were selected, which together represented 79 % of the energy use of the industrial sector in 2012 [48]. For each of these sectors (Figure 3.4), the energy input from 16 different fuel types (e.g. oil, natural gas, biogas), electricity, district heat and heat pumps was available. In addition, previous publications by the Danish Energy Agency [111] provided the distribution of fuels and district heating amongst 10 process categories, such as distillation, heating, evaporation, drying and conversion and transmission losses. The electricity input was distributed between 13 final processes. The end-consumers for transportation within the industry sector were not considered.

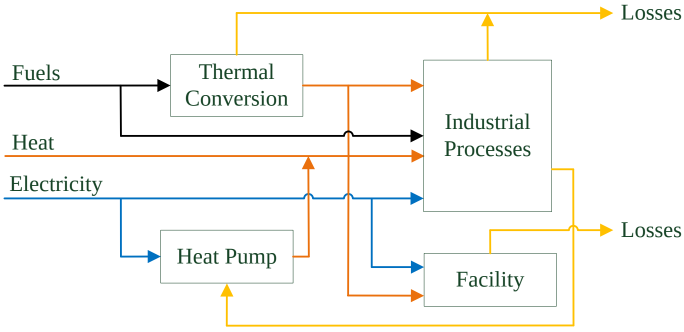


Figure 3.4: Processes and energy flows within an industry sector.

Utility sector

The utility sector (Figure 3.5) was also taken into account. In Denmark, electricity from thermal power plants was in 2012 to a large extent produced in combined heat and power (CHP) plants, using primarily coal, natural gas and biomass. Furthermore, a share of 29 % of the net electricity produced originated from wind power and 15 % was from net imports from the neighbouring countries (e.g. Germany, Sweden and Norway) [112]. Almost 74 % of the district heat was produced in CHP units and the remaining part in heating units. The data from the Danish Energy Agency [112, 113] also gives information on the self-consumption of the power plants, as well as on the distribution and transmission losses.

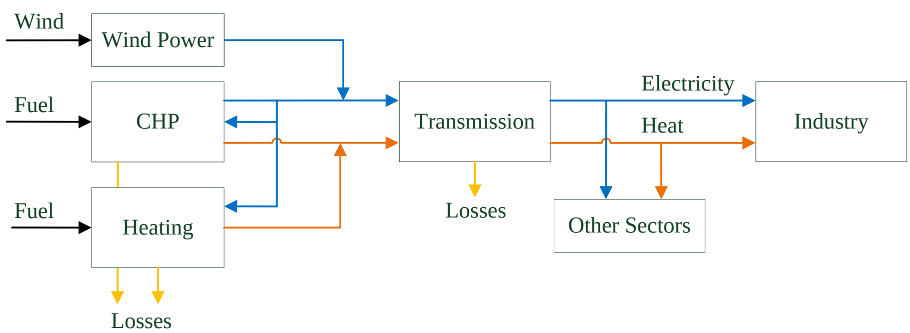


Figure 3.5: Processes and energy flows within the utility sector.

3.2.2 Energy and exergy efficiencies

The energy (η) and exergy (Ψ) efficiencies of the system are defined below, as the sum of energy or exergy in the product, divided by the total energy or exergy input to the system.

$$\eta = \frac{\text{energy in product}}{\text{total energy input}} \tag{3.1}$$

$$\Psi = \frac{\text{exergy in product}}{\text{total exergy input}} \tag{3.2}$$

The efficiencies in this work were classified into site and system efficiencies, the latter including the utility processes. From Figure 3.6 the applied system boundaries can be seen, where the system efficiency includes losses from the utility system. The efficiencies were further subdivided on the site level based on the end-use. Four end-use categories were established: thermal and machine processes, as well as thermal and electric facility use. In the following sections the equations for the efficiencies are shown in more detail.

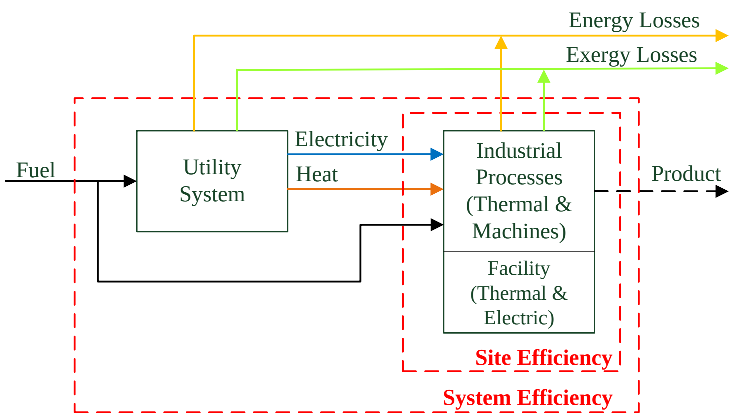


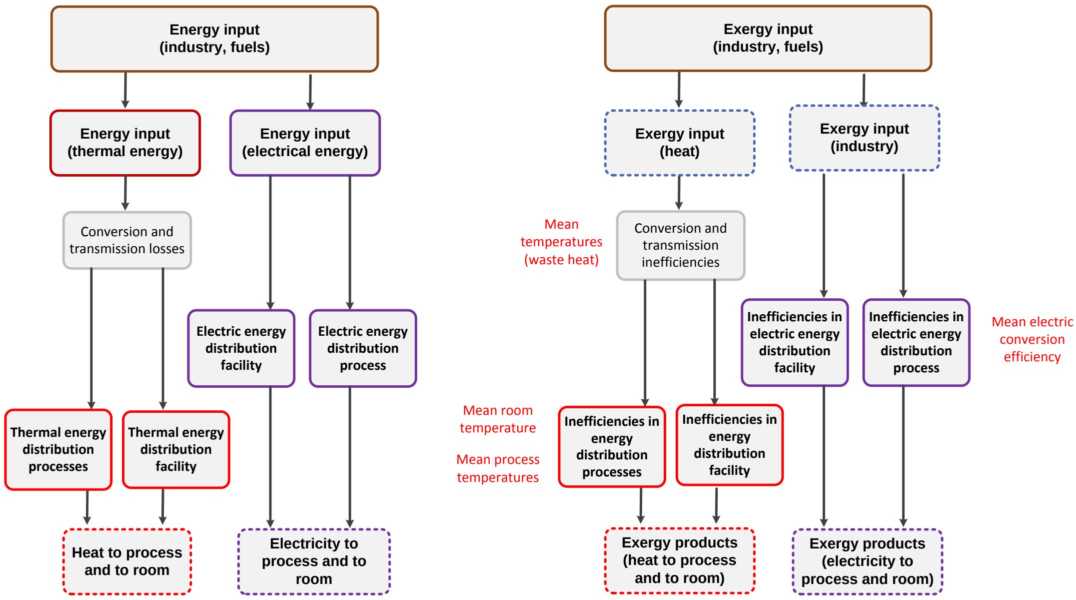
Figure 3.6: System boundaries for site and system efficiency.

3.2.3 Application

In the following, the applied techniques are explained for the case of the industrial and utility sectors of Denmark, and the sources of losses and exergy destruction are pointed out.

Industrial sector

Global approach Figure 3.7 shows the overall approach for the determination of energy and exergy losses and the exergy destructions for the industry sector. For each of the 22 industry sectors, the fuel consumption for all individual process categories was distributed amongst three temperature levels and for each level, the mean process temperature was determined. The process information used to establish this distribution and the mean temperatures originated from several sources, with the main ones being the Danish Energy Agency [111, 114], the European Commission [115], the Graz University of Technology [116], and the U.S. Environmental Protection Agency [117].



(a) Energy Analysis (b) Exergy Analysis

Figure 3.7: Flow chart of the methodology for the analysis of the industrial sector with the fuels and considered processes.

The energy losses derived from (i) the conversion and transmission losses, and (ii) the direct use of fuels and electricity. The former were determined by the Danish Energy Agency [111, 114]. They accounted for the conversion of fuels to a secondary energy carrier, which was supplied to the processes. Transmission losses occurred primarily in the steam and hot water distribution systems. The magnitude of these losses differed from sector to sector: it was impacted by the process type and the share of space heating within the total heating demand. The heat rejected to the environment (waste heat) had a temperature of up to 260 °C. It did, however, not exceed 150 °C for about 50 % (45 % in 2006) of the sources, since waste heat recovery equipment was installed [118, 119].

The second type of energy losses resulted from the direct use of fuels and electricity in the process and thermal losses of high-temperature processes. Examples of these processes are drying of gravel in direct-fired dryers or melting of metals in furnaces, where the energy used within the sector is directly utilised in the process. The efficiency for direct process heating is dependent on the process temperature and is presented in Table 3.1. The applied efficiencies were based on Rosen [43] and Dincer et al. [108] but were adjusted to Denmark. For temperatures below 120 °C, the fuel heating efficiency was 100 %, as this heat was almost fully supplied by secondary energy carriers for which the conversion and transmission losses were applied. The values of the waste heat temperatures for the losses in the direct conversion and high temperature components were based on literature data [119, 120].

Table 3.1: Energy efficiency for heating with fuels and electricity used in the industry sector.

	Range	Direct Heating Efficiency	
		Electrical	Fuel
	[°C]	[%]	[%]
Low	≤ 120	100	100
Medium	120 - 380	90	85
High	≥ 380	75	70

For electricity use in machinery and the facilities (excluding process and space heating), efficiencies for the conversion were taken from Hvenegaard et al. [121], assuming large-scale units with an average load rate between 70 % and 80 %.

Process heat and space heating First, the thermal energy used for the processes $\dot{Q}_{pr}$ was determined based on the energy distribution for the different processes. The losses for fuel conversion were subtracted, and for the direct use of fuels and electricity, the efficiency was defined based on the temperatures as shown in Table 3.1.

$$\sum_{i,j} \dot{m}_{Fi,j} \, (\mathrm{LHV})_i = \sum_{i,j} \dot{Q}_{pr\,i,j} + \sum_{i,j} \dot{Q}_{Li,j} \tag{3.3}$$

The exergy in the product $\dot{E}_P^Q$ was found with Eq. 3.4 based on the average process temperature T_{pr} and the thermal energy $\dot{Q}_P$ of the product. The exergy losses $\dot{E}_L^Q$ were found in the same manner as a function of the mean waste heat temperature T_L and the thermal energy loss $\dot{Q}_L$ (Eq. 3.5. The rate of exergy destruction $\dot{E}_D$ of each process and fuel was found by subtracting the exergy in the product and losses from the total exergy into the process $\dot{E}_F$ (Eq. 3.6).

$$\dot{E}_P^Q = \left(1 - \frac{T_0}{T_{pr}}\right) \dot{Q}_P \tag{3.4}$$

$$\dot{E}_L^Q = \left(1 - \frac{T_0}{T_L}\right) \dot{Q}_L \tag{3.5}$$

$$\dot{E}_D = \dot{E}_F - \dot{E}_P^Q - \dot{E}_L^Q \tag{3.6}$$

Process and facility electric use The use of electricity in processes and facility was based on the electric efficiency of the units η_{el}. The useful work $\dot{W}$ retrieved from the electric energy in $\dot{W}_{el}$ was calculated using Eq. 3.7. As mechanical and electric work are equal to the exergy of work and electricity, Eq. 3.7 also applied to the exergy calculations.

$$\dot{W} = \eta_{el} \dot{W}_{el} \tag{3.7}$$

Efficiency of each industry sector For each sector, the process heating efficiency $\eta_{pr,h}$ was defined as the ratio of the sum of the thermal energy in the products and the total energy input to the thermal processes in the sector.

$$\eta_{pr,h} = \left(\frac{\sum_j \dot{Q}_{P,j}}{\sum_i \dot{m}_{F,i}\,(\mathrm{LHV})_i} \right) \tag{3.8}$$

where $\dot{Q}_{p,j}$ denotes the heat transfer associated with the process j; $\dot{m}_{F,i}$ the mass flowrate of the fuel i; $(\mathrm{LHV})_i$ is the lower heating value of the fuel i.

Similar to the energy efficiency, the exergy efficiency for process heating $\Psi_{pr,h}$ was defined as:

$$\Psi_{pr,h} = \left(\frac{\sum_j \dot{E}_j^{Q_P}}{\sum_i \dot{m}_{F,i}\phi_i\,(\mathrm{LHV})_i} \right) \tag{3.9}$$

where $\dot{E}_j^{Q_P}$ denotes the exergy transfer associated with heat transfer $Q_{P,j}$ of the process j; ϕ_i is the fuel to exergy ratio of the fuel i.

For the electric heating efficiency, the sum of heat transfer for the processes was divided by the electric work into the system. For the exergy electric heating efficiency, the exergy transfer associated with the heat transfer was used. The efficiency for the use of mechanical work in the processes was derived with the following equation, where the energy ($\eta_{pr,el}$) and exergy ($\Psi_{pr,el}$) efficiency were equal.

$$\eta_{pr,el} = \Psi_{pr,el} = \left(\frac{\sum_j \dot{W}_j}{\sum_j \dot{W}_{el,j}} \right) \tag{3.10}$$

where $\dot{W}_j$ denotes the work of the process j; $\dot{W}_{el,j}$ is the electrical work into the process j.

For the facilities, the efficiencies were found by analogy to the process efficiencies, with the energy ($\eta_{fa,h}$) and exergy ($\Psi_{fa,h}$) efficiency for the heating processes within the facility, as well as for the electricity use ($\eta_{fa,e}$ and $\Psi_{fa,e}$).

Utility sector

Global approach The aim of the analysis of the utility sector was to find the system energy and exergy losses, as well as the exergy destruction, for electricity and district heat. This approach was similar to the one of Szargut et al. [122] for the cumulative consumption of non-renewable exergy in manufacturing and of Granovskii et al. [123] for the exergy life cycle assessment, applied to hydrogen production from renewable sources. Further, Cornelissen and Hirs [124] showed the value of using exergy life cycle assessment at the example of waste wood treatment and Stougie and Kooi [125] evaluated the relation between exergy losses and environmental. This analysis, however, takes only energy and exergy transformations of the fuels, within the utility and industrial sector, into account.

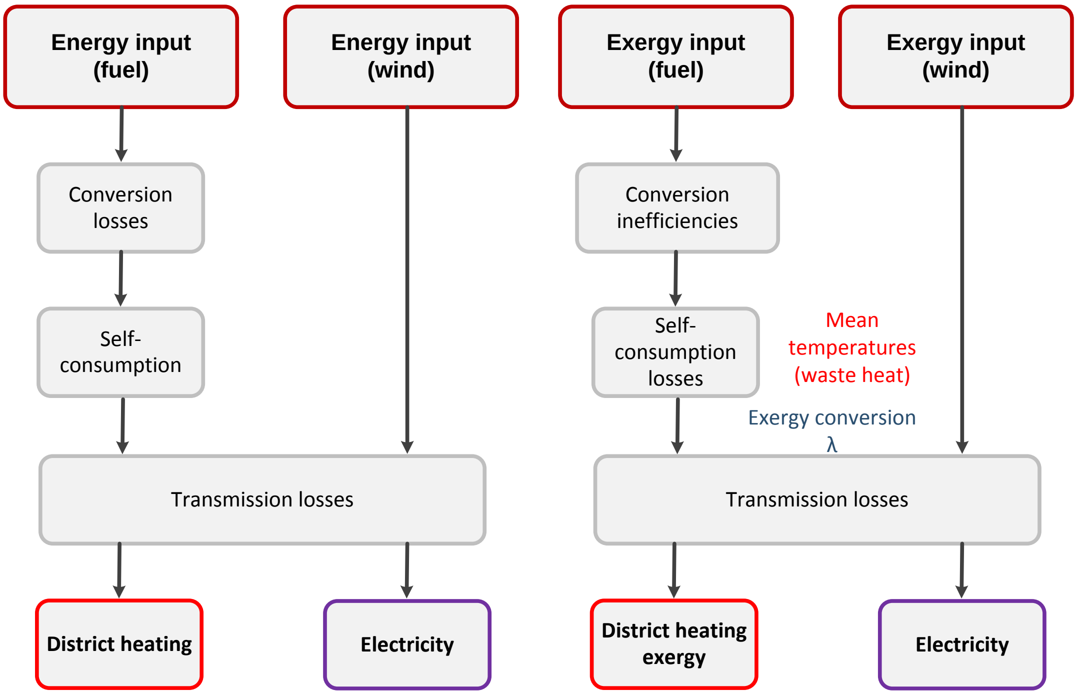
In Figure 3.8 the approach for the analysis of the utility sector is shown. There were three sources of energy losses, namely conversion, transmission and self- consumption. When considering exergy, losses only occurred in the form of excess heat contained in the flue gases from the power plants since the internal energy losses were accounted as exergy destruction. The average temperature of the flue gases was taken as 150 °C [126] and was assumed constant, although it changes in practice with the fuel used in the combustion process. The excess heat discharged through the condenser of steam power plants was neglected, as it was rejected at low to very low temperatures (around 30 °C). Exergy is destroyed in the conversion of the fuels to electricity and district heat, the off-gases from the power plants, and with the transmission losses and self-consumption. The transmission losses of the district heating distribution pipes were assumed to be close to the dead state temperature, implying that very little exergy could be recovered.

In the case of electricity from wind energy, only the transmission losses were taken into account. Import and export of electric energy were not considered in this study, as they balance on a long term basis. For each utility system, the required fuel input for the generation of one unit electricity and district heat was found. The fuel allocation, in the case of CHP production, was done based on the product distribution. The allocation of the exergy destruction and losses to the final exergy products delivered to the industry follows the same reasoning, with a separation between the destruction and losses.

Electricity and district heat from the utility sector For CHP plants, the energy balance used was as follows:

$$\sum_i \dot{m}_{F,i}\,(\mathrm{LHV})_i + \dot{W}_{el,\mathrm{SC}} = \dot{W}_{el} + \dot{Q}_{\mathrm{DH}} + \dot{Q}_L \tag{3.11}$$

The reformulation of the energy balance was done for the losses similar to the thermal processes within the industry. The exergy destruction within the power plant was found as the difference between the product and loss exergy content and the exergy into the system.



(a) Energy Analysis (b) Exergy Analysis

Figure 3.8: Flow chart of the methodology for the analysis of the utility sector with the fuels and considered processes.

System energy and exergy efficiencies The system energy ($\eta^{sys}_{pr,h}$) and exergy ($\Psi^{sys}_{pr,h}$) efficiencies accounted for the generation and transmission losses associated with the production of electricity and district heat. They were defined as the sum of exergy or heat contained in the product, divided by the sum of the direct energy or exergy input at the thermal site and the indirect input at the utility sector for the supply of district heat and power. The efficiencies were expressed as follows:

$$\eta^{sys}_{pr,h} = \frac{\sum_j \dot{Q}_{P,j}}{\sum_i \dot{m}_{F,i}\,(\mathrm{LHV})_i + \sum_n \dot{m}_{F,ni}\,(\mathrm{LHV})_n} \tag{3.12}$$

$$\Psi^{sys}_{pr,h} = \frac{\sum_j \dot{E}^{Q_P}_j}{\sum_i \dot{m}_{F,i}\phi_i\,(\mathrm{LHV})_i + \sum_n \dot{m}_{F,n}\phi_n\,(\mathrm{LHV})_n} \tag{3.13}$$

With the same approach, the efficiencies for the generation of work and heat in the facilities were found.

3.3 Results

The results of the analysis are presented in the following. First, the industrial site analysis is shown, followed by the system analysis and the quantification of exergy losses for the year 2012. At the end, a comparison of the results with data from 2006 was performed. In Table 3.2, the total energy consumption of the industrial sectors is shown for the analysed years 2006 and 2012. The two industries with the highest process heating demand were the oil refineries and the production of cement. Despite the general trend that for most industries the energy input decreased between 2006 and 2012, some sectors such as the wood industry had an increase. This was partly a result of production changes and of a different sectoral distribution by Statistics Denmark (i.e. sector 15). In total, the energy consumption was reduced by 16 % between 2006 and 2012.

Table 3.2: Total energy use of the industries considered in 2012 and 2006 in [TJ]. Distributed according to Danish Energy Agency [111, 114] and data from Denmark Statistics [48].

No.	Industry	Process Heating		Machine Drive		Facility	
		2012	2006	2012	2006	2012	2006
1	Refined oil	16789	17142	1020	742	66	46
2	Meat	1855	1762	1094	1646	904	892
3	Dairy products	3394	3332	1298	1001	776	595
4	Compound feed	1158	1460	658	839	221	288
5	Sugar	2725	3285	354	172	140	239
6	Other food products	2403	3530	999	1355	444	693
7	Wood	2706	2082	585	962	718	1060
8	Paper	1770	2183	559	986	284	373
9	Industrial Gases	-	-	399	447	60	69
10	Enzymes	1026	1191	875	1028	195	292
11	Other chemicals	520	562	707	654	304	361
12	Pharmaceuticals	1592	1208	1289	1146	264	1640
13	Plastic and rubber	897	1737	965	1189	913	1770
14	Paint, soap etc.	3065	734	1006	807	353	930
15	Gravel and stone	2847	3819	326	283	43	88
16	Cement	9116	14734	1038	1703	52	85
17	Bricks	1310	1334	119	134	14	15
18	Asphalt	1343	1252	96	108	77	69
19	Rockwool	1666	2257	293	330	76	72
20	Concrete and bricks	2273	1956	275	309	270	281
21	Basic metals	2187	2807	386	728	421	780
22	Metal products	1326	2132	856	1129	1490	2769

The share of fuel and electricity of the total energy use within the industry can be seen in Figure 3.9. Here, the fuel consumption was split in process fuel and heating fuel. In the chemical industries the share of electricity was the highest in most of the sub-sectors, whereby the building sector was dominated by process fuel use. District heating accounts for 4 % of the total energy input to the industry, of which 6 % were used as process heat and the remainder for space heating.

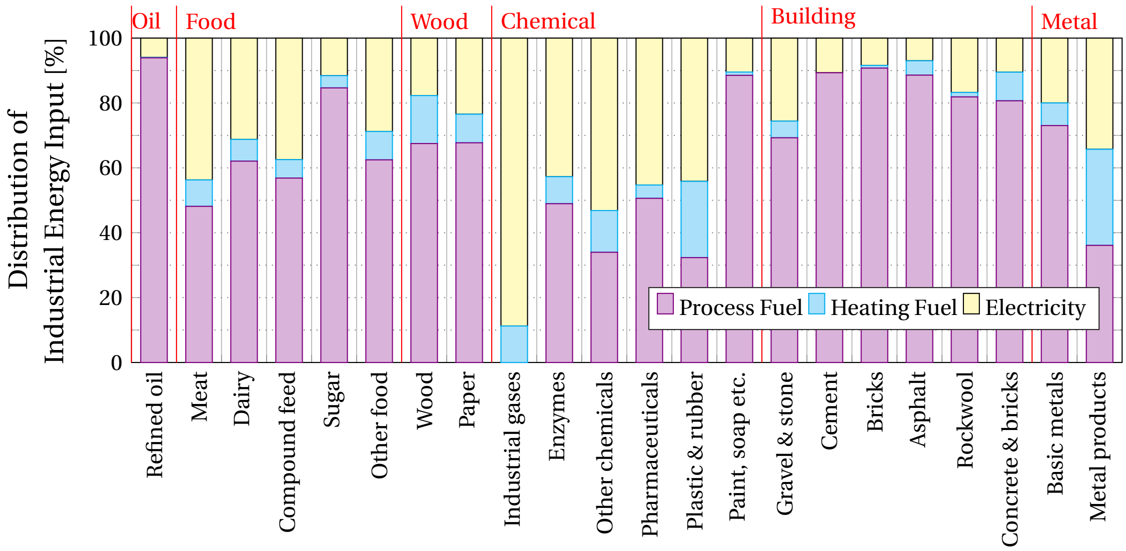


Figure 3.9: Share of different energy carriers used in the industrial sectors in 2012.

3.3.1 Site analysis of the industrial sector

The energy and exergy efficiencies for all thermal processes occurring in the industrial sectors in 2012 are shown in Figures 3.10 and 3.11, respectively. For heating processes in the facilities, high energy efficiencies were achieved, where industries using electric and district heat reached the highest ones. In exergy terms, the efficiency was the lowest for the facilities because of the low product temperatures of space heating.

For the thermal use of energy within industrial processes, energy efficiencies above 70 % were found for all sectors. Sectors with high-temperature operations and the direct use of fuels for processes, i.e. sectors within metal and building material production, had the lowest efficiencies. For those sectors, high exergy efficiencies were found, as the high temperature operations increased the exergy content in the products. Only sector 20 had a comparably low exergy efficiency, as it included the production of concrete elements and gypsum plates, where thermal energy is required at lower temperatures. The overall exergy efficiencies ranged from 10 to 55 % for thermal processes, excluding sector 10 (industrial gases), where no thermal processes occurred in the production.

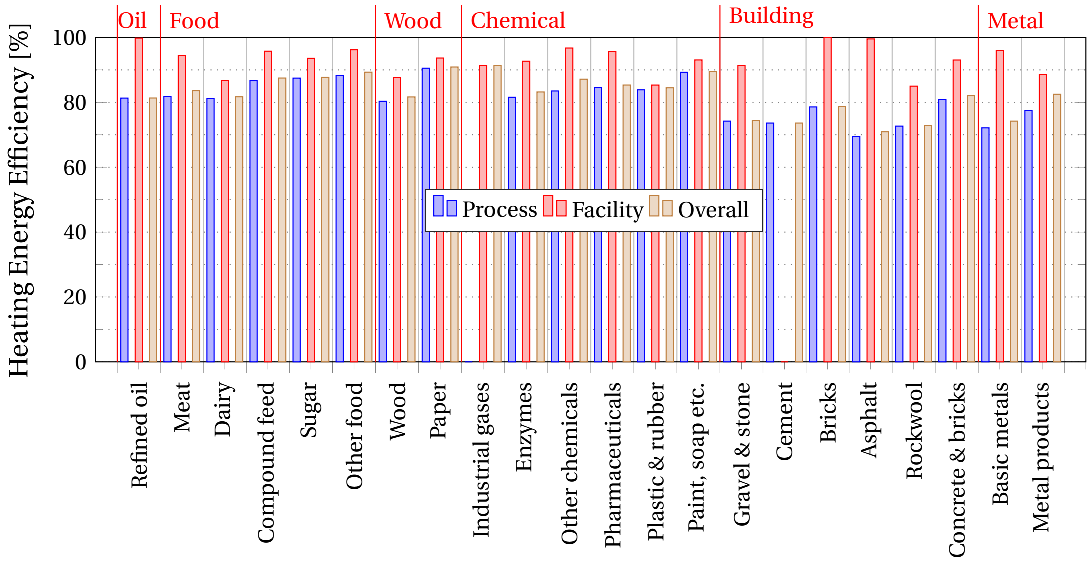


Figure 3.10: Energy efficiencies within the industry for thermal heating in processes, facilities and overall, as the weighted average.

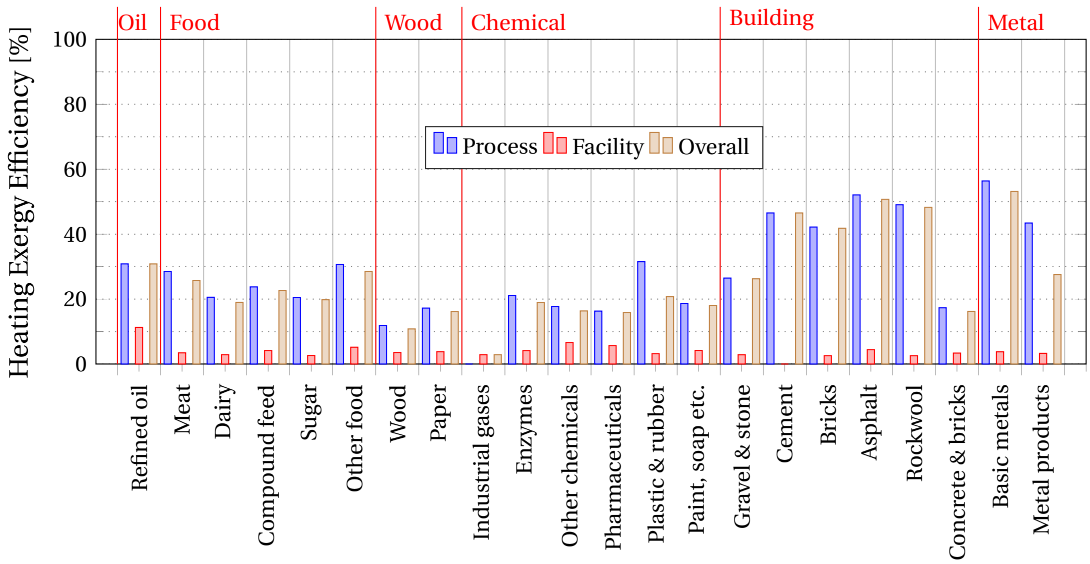


Figure 3.11: Exergy efficiencies within the industry for thermal heating in processes, facilities and overall, as the weighted average.

The comparison of the energy and exergy efficiencies for process heating shows that exergy can give more insights. The example of space heating suggests that the process was already close to its optimum, as very high energy efficiencies, between 85 % and 100 %, were retrieved. However, the very low exergy efficiency of space heating, below 10 % for most industries, revealed that considerable potential for improvement existed. Higher exergy efficiencies could be achieved by using low exergy sources for low temperature heating processes. This could be for instance district heat or heat recovered from high temperature processes. With these measures not only the space heating, but also the processes could be designed more efficiently.

3.3.2 System efficiency of the industrial sector

The exergy efficiencies, including losses of district heat and electricity occurring at the central power stations and during transmission, are shown for the total thermal and electric energy use in Figure 3.12. A comparison of the total site and the total system exergy efficiencies is done in Figure 3.13, where all heating and mechanical processes are included. The system

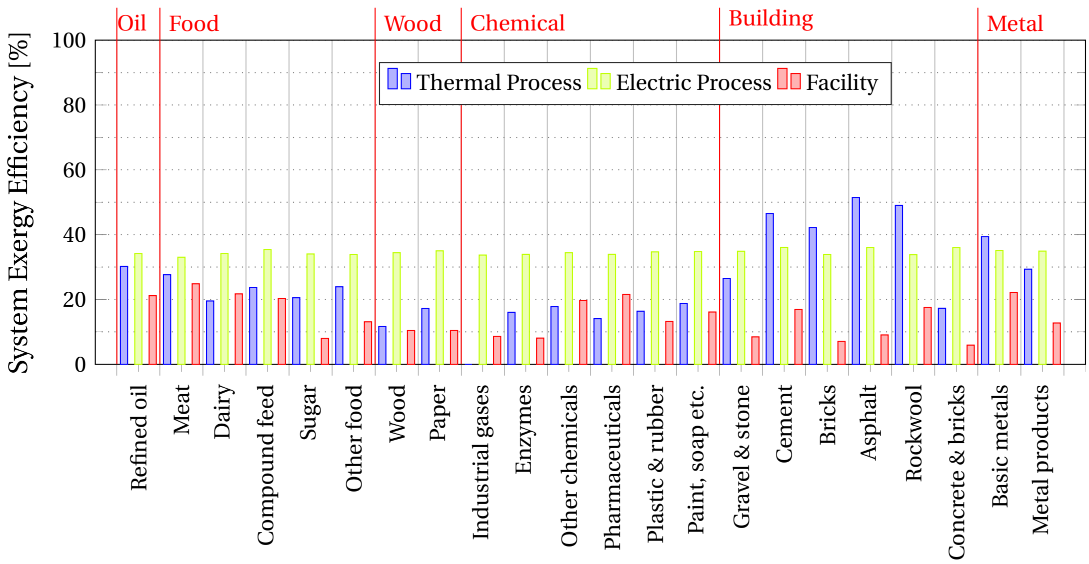


Figure 3.12: System exergy efficiencies for thermal and electric processes and facility within the industry sector (2012).

exergy efficiency for electric processes was nearly constant over all the sectors, as it was a direct function of the electric energy efficiency. However, the thermal exergy efficiency was much lower for several industries. For the metal processing industries, which had the highest thermal site efficiencies, the system exergy efficiency was considerably reduced. Within the food and chemical industry, no considerable reductions were found as most of the thermal energy originated from natural gas and other fuels.

Figure 3.13 shows a comparison of the total site and total system exergy efficiency, taking into account all heating and electric processes. The production of industrial gases had the highest site efficiency but the system efficiency was only half, as this industry used primarily electric energy. Similar differences in the efficiency were found for the food and metal industry, where the production relied on electricity and district heat. In contrary, industries such as oil refinery, sugar, cement and brick production had only small differences in the site and system efficiency. The system exergy efficiency was further higher in the building material industry. By using the system exergy efficiency and thereby extending the system boundaries,

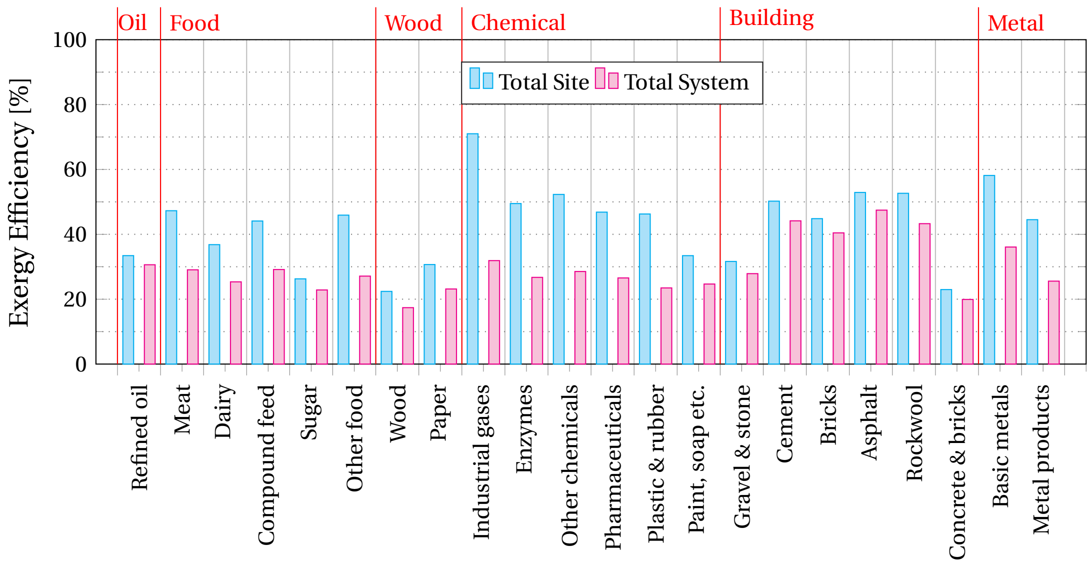


Figure 3.13: Total site and system exergy efficiencies for exergy use in processes and facilities within the different industry sector (2012).

it was possible to account for all the losses occurring in the industry. These system exergy efficiencies are important indicators for a system analysis, and can be used to assess the most optimum energy sources for the production. For some industries, e.g. production of industrial gases, the possible actions were limited as there was no alternative to the use of electricity in the processes.

3.3.3 Exergy loss and destruction

The analysis of exergy loss and destruction shows the recovery potentials in the industries. This is possible as the exergy content of the stream describes the maximum work which can be retrieved. Figure 3.14 presents the share of exergy loss and destruction of the total site exergy input for the thermal conversion in the industry. The production of building materials had the largest potential, with the exergy loss being up to 10 % of the total thermal input. Significant potentials of above 5 % were also found in the food, wood, paper and chemical industry.

In Figure 3.15 the exergy loss and system exergy loss for each industry is shown for the thermal processes and machine drives. The industries with the highest energy input, also had the highest exergy loss on site. However industries with a high electric energy consumption, almost reached the same total exergy losses, such as the production of meat and dairy products.

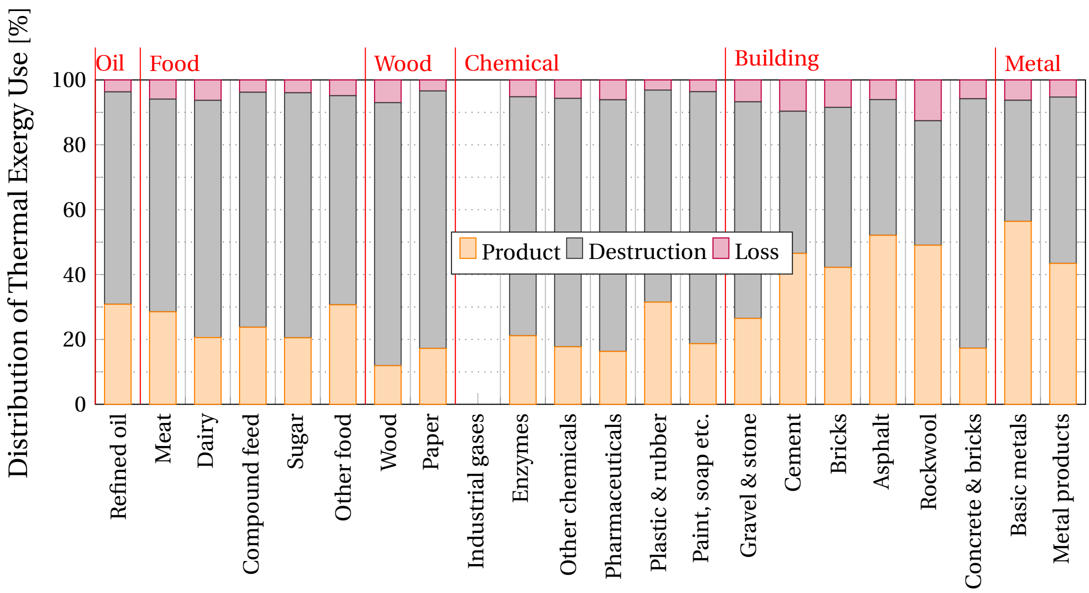


Figure 3.14: Distribution of exergy for process and facility heating within the industry sector (2012).

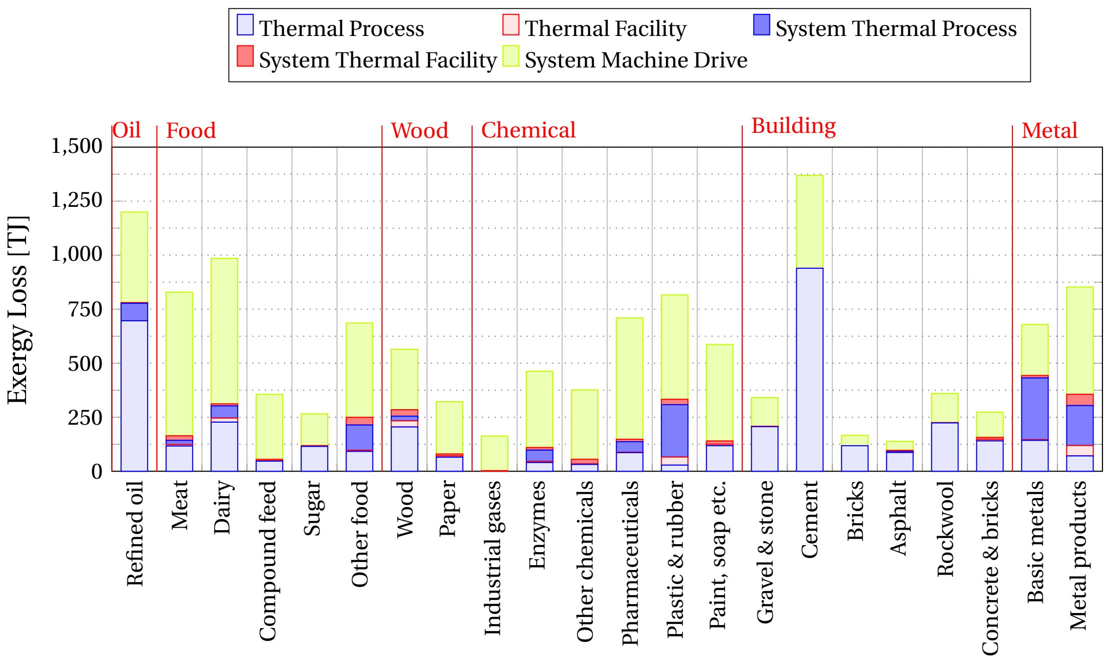


Figure 3.15: Exergy loss divided by source for the different industrial sectors (2012).

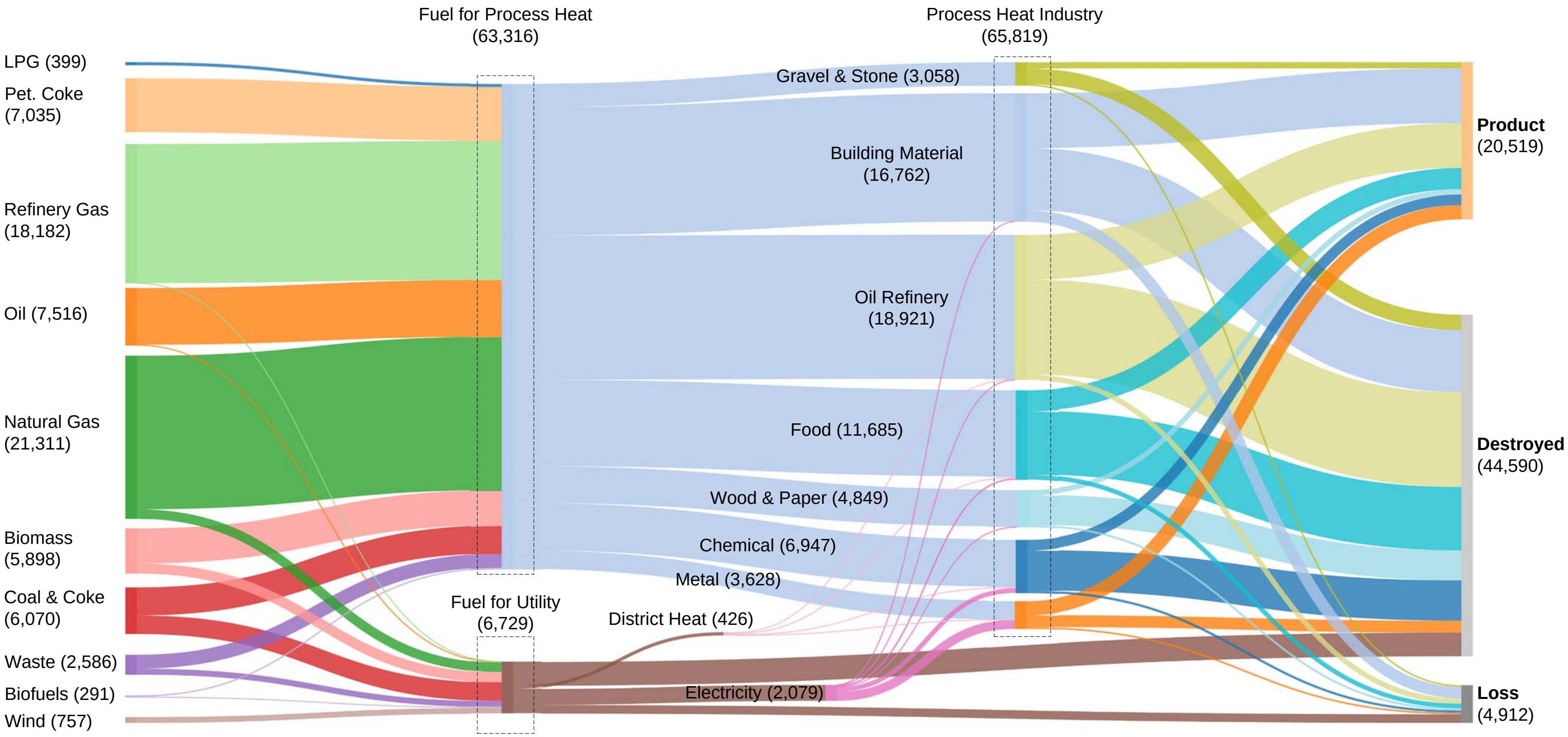


Figure 3.16: Exergy flows for process heating within the industry sector in TJ (2012).

In total, approximately 3800 TJ of exergy were lost from thermal processes within the industry and an additional 200 TJ in the supply of space heating. The production of cement and the refinery of oil had together an accumulated exergy loss of 1600 TJ from thermal processes. In these industries possibilities of more process integration and the export of heat should be considered, by implementing heat recovery systems.

For most industries, the majority of the exergy loss was associated with the electricity used in machines. Only the production of basic metals and metal products, as well as the rubber and plastic production had a considerable exergy loss for thermal processes, due to the use of electricity for heating.

The overall exergy flows for thermal processes in the industry are shown in Figure 3.16 and confirmed the previous findings. Only a small fraction of the total exergy destruction (7 %) resulted from the utility sector. The majority of the lost exergy originated from the production of building material and oil. In total, an exergy loss for thermal processes of almost 5000 TJ was found when including the losses associated with the utilities. The system losses could be reduced by increasing the share of wind energy and the production of district heat.

The exergy losses, as found in this section, describe the potential of exploiting the energy associated with the stream currently discharged into the environment. These losses could be reduced by further process integration and waste heat recovery. For example, the implementation of heat pumps and organic Rankine cycles would result in the conversion of low-temperature heat into district heating and electricity.

Comparison of 2006 and 2012 A comparison of changes in efficiency between 2006 and 2012 for the main industry groups is shown in Figure 3.17. On a site level the efficiency increased for most industries by up to 3.9 %-points. A considerable reduction in efficiency was seen for the wood processing industry, which was caused by structural changes causing a decrease in electricity consumption for machine drives. This caused a higher weighting of the thermal processes, which had a lower efficiency. Using the system exergy efficiency, also the wood industry had an increase in efficiency, as the losses from electricity use were smaller.

Considering the overall efficiencies for the Danish industry as a whole, found as the weighted mean efficiencies of all sectors, a clear improvement could be found from the first law analysis for almost all efficiencies, as can be seen in Table 3.3. For the exergy analysis, the efficiency of the thermal processes has decreased, whereby the total exergy efficiency has increased slightly. This increase was a result of the improved use of electricity in the facilities, which had a strong weight on the result due to its high exergy value.

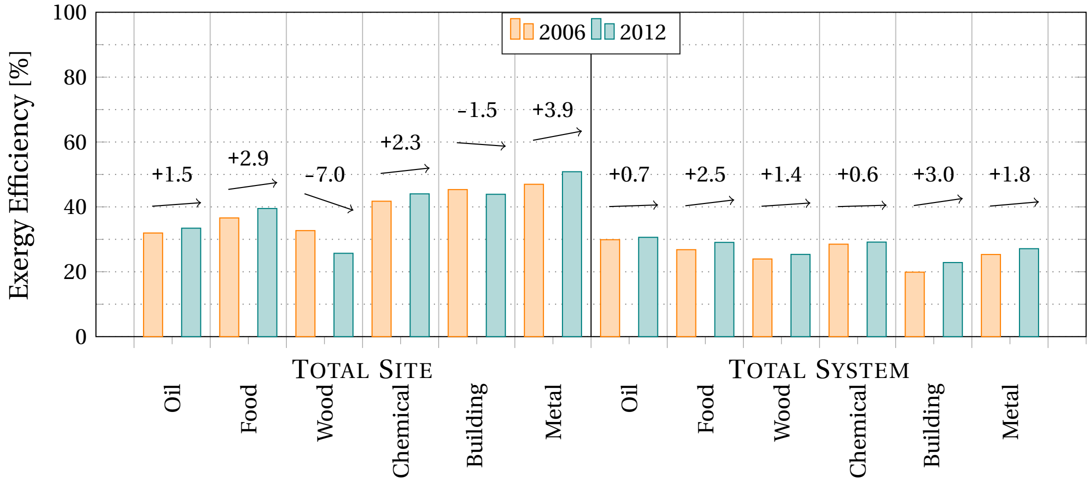


Figure 3.17: Change in the total site and total system exergy efficiency for industry groups between 2006 and 2012.

Table 3.3: Total industry efficiency of the Danish industrial sector for 2012 and 2006, found as weighted mean efficiency. The terms SiEX, SyEX, SiEN and SyEN stand for site exergy, system exergy, site energy and system energy.

Efficiency [%]	SiEX		SyEX		SiEN		SyEN	
	2012	2006	2012	2006	2012	2006	2012	2006
Thermal Processes	31.2	32.6	29.3	30.6	80.3	78.8	77.8	75.8
Thermal Facility	3.6	3.5	2.7	2.7	90.9	90.3	78.1	73.2
Electric Processes	81.4	81.6	34.0	32.4	81.4	81.6	57.2	47.3
Electric Facility	64.3	60.3	27.2	23.9	64.3	60.3	45.2	34.9
Total	39.7	39.7	29.6	28.8	80.6	79.7	71.8	66.4

3.3.4 Process heating demand

Using the developed model and method, it was also possible to analyse the process heating demands of the industrial sectors. The exergy analysis required the establishment of temperatures for the exergy product, $\dot{E}_P^Q$. These temperatures were allocated to the process heat demands, which allowed the analysis of temperature requirements for process heating. Figure 3.18 shows the low temperature heating demand by industry sector and process temperature. These heating demands could be in theory covered by heat recovery in the industry or other low temperature heat sources (e.g. solar, heat pumps and geothermal). Despite the majority of the thermal process heating demand being above 150 °C, there was a heating demand between 70 °C and 100 °C in the food, chemical and pulp & paper industry.

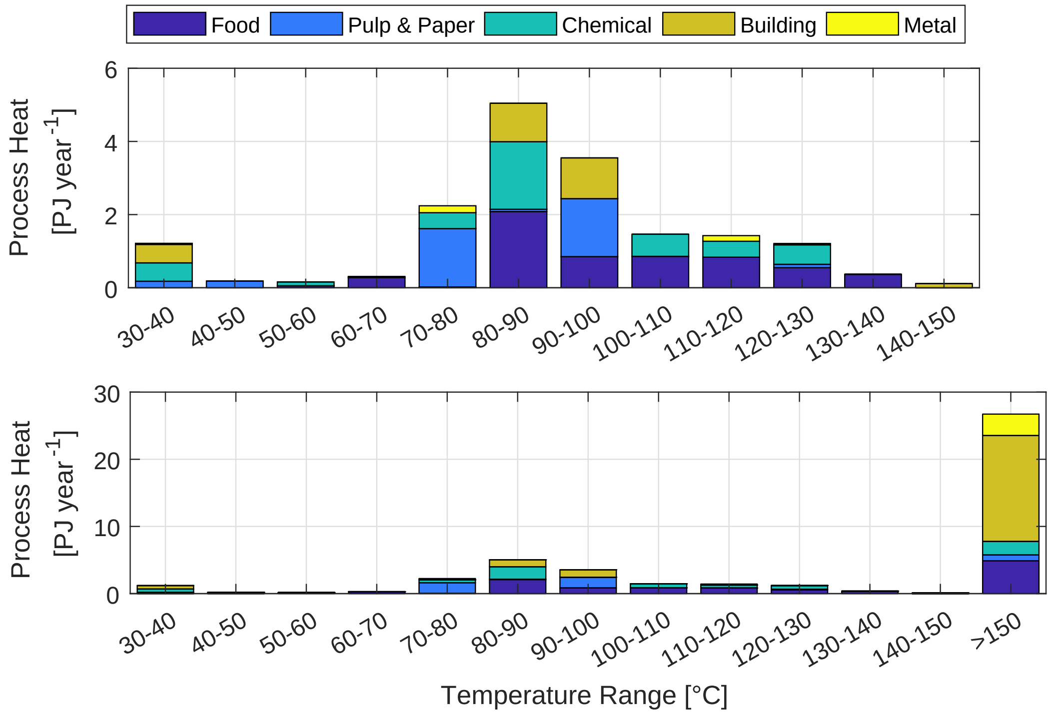


Figure 3.18: Process heat demand by temperature level and industry in 20012.

3.4 Discussion

3.4.1 Uncertainties and limitations

This sectoral analysis was subject to some uncertainties in the used data and applied method, which are discussed in the following. The distribution of the fuels amongst the categories was based on the Danish Energy Agency [113, 114], where detailed information of the energy consumptions of the main companies of each sector was used. If no information was available, processes representing the sector and assumptions were undertaken. These distributions were representative for homogeneous industry sectors, but for sectors such as 'Other food products' and 'Other chemicals', assumptions and generalisations had to be made. The same applies for the process temperatures and their distribution. In particular, for the production of pharmaceutical products, enzymes and other chemicals, insufficient information was present to create a precise end-use model. The implications of the resulting uncertainties are small for the energy efficiencies, as the process temperatures in these industries were mainly below 125 °C, for which the direct heating efficiency was chosen to be between 85 % and 100 %. The exergy efficiency, however, is related to the process temperature and changes with a varying fuel distribution amongst the process temperatures. For the most critical sectors, the temperatures were nevertheless in a similar range of 50 °C to 125 °C and did not include any high temperature processes.

The data of 2006 and 2012 are not directly comparable for all sectors and some assumptions had to be made. Statistics Denmark reorganised the industry classification in 2008, and, as a result, some industries were allocated to new sectors. Furthermore, structural changes within some sectors and different economic developments were not taken into account. The production of combined heat and power within the industry was neglected in this study, as insufficient data was available. The calculation of the exergy losses was nonetheless not impacted by these limitations, as the basic data did not include the fuels for heat and power production on the industrial site.

For the energy in electricity and district heat, the allocation of primary energy was based on the product distribution. As in the case of the first law analysis, the value of the products was identical, the fuel consumption in the product was the same. For exergy, the allocation of the input to the utility sector was distributed based on the exergy content of the products. This results in a higher allocation of the input to the electricity production, than in the energy analysis. However, as more exergy is destroyed in the production of district heat, the specific exergy destruction per unit of exergy is higher for district heating.

3.4.2 Method and results

The total process heating efficiency for the Danish industry was in the same range as for other countries, amongst others Iran [107], Saudi Arabia [108] and South Africa [109], where exergy process heating efficiencies of around 30 % were found. The energy efficiency for both process heating and the total site were however higher in this study, compared to values between 50 % and 70 % in the other studies. This is primarily a result of the higher direct process heating efficiencies chosen in this study. The same applies on a sectoral level, where similar exergy efficiencies were found for comparable industries, but higher ones for energy.

Other studies have used large definitions of industrial sectors, such as Chemical & Petroleum [109]. The disaggregation of this sector into seven sub-sectors, as done in this study, shows that efficiencies can vary considerably. The production of industrial gases reached a total site exergy efficiency of 70 %, whereby oil refineries were below 35 %.

The inclusion of inefficiencies occurring in the utility sector allows, a more valid comparison of industrial sectors and the use of fuels with electricity and district heat. Based on the system efficiency, continuous efforts should be made to avoid electric heating if the electricity originates from other sources than wind power.

By using the method applied in this study, a complete comparison of industries and countries is possible, also taking into account the efficiency of the national utility system. This allows to track the development of the industries over time and to target efficiency and waste heat recovery measures on a national level. The high level of detail in the model makes it further possible to find inefficiencies on a process level and to quantify the real recovery potential.

3.5 Conclusion

This chapter analysed the energy and exergy efficiency, as well as the destroyed and lost exergy, of 22 industrial sectors in Denmark for the years 2006 and 2012. By using the distribution of fuels and temperature levels for different processes within the sectors, a detailed end-use model for the thermal energy use for individual industries was created. The utility sector was included in a further approach to find the system exergy and energy flows, for electricity and district heat supplied to the industry.

The main conclusions from the case study were, that the share of lost exergy found in the thermal processes within the industry suggested large potentials for waste heat recovery. The lost exergy from the central production of heat and power was considerable higher than the losses on-site, as the use of electric energy for machines was included in the losses.

In 2012 for individual industries, the thermal process efficiencies ranged from 12 % to 56 %, where industries with high temperature processes such as cement and metal production achieved the highest efficiencies. The energy efficiency was between 63 % and 90 %, the less efficient industries were characterised by high-temperature processes, and the most efficient ones were the food, paper and chemical industry. On an industry level, the total exergy efficiency was approximately 40 % with the system exergy being around 10 % points lower. A comparison of the years 2006 and 2012 showed no remarkable improvements on an exergy level, but the energy efficiency was considerably improved.

It is suggested that future actions towards energy efficiency measures in the industry, target the high temperature processes, where large quantities of energy are recoverable. Furthermore, the use of district heat and heat pumps for low temperature processes would improve the site efficiencies. Although the share of district heat and heat pumps has increased between 2006 and 2012, the improvement was not notable in the total efficiency.

Moreover, this chapter gave a basis for future analyses of the industrial sectors, and the application of the method was described in detail. The importance of including the system efficiencies was shown. The additional information, which can be obtained by disaggregating sectors and determining exergy losses and destruction, has shown to be useful when locating excess heat potentials.

4 Mapping of excess heat

In this section the general approach to the mapping of excess heat is described. First a general mapping of excess heat for the transport, utility, building and industry sectors in Denmark is presented. Afterwards a more detailed analysis of excess heat in the manufacturing industry is shown. The overall aim is to quantify the amounts and temperatures of excess heat available from different sectors and to present the main assumptions and methods.

4.1 Introduction

Low temperature heat sources are available in many applications, ranging from excess heat from industrial processes and buildings to geothermal and solar heat sources. Technical advancements, such as heat pumps with novel cycle design and multi-component working fluids, make the utilisation of many of those heat sources feasible.

A number of studies, such as the ones from Reistad [94] and Utlu and Hepbasli [101], and the previous chapter analysed the overall energy and exergy utilisation of countries and for specific sectors. The focus was on the overall sector efficiencies and on the conversion processes in the utility system. Those studies showed that there were large amounts of energy and exergy losses, in particular from the industry sector which need to be analysed in more detail. These losses are, in a thermodynamic sense, streams of matter (e.g. water or air) at a higher temperature than the ambient. These losses can be reduced by using these wasted streams for covering the existing heating demands or producing additional power. Excess heat sources at specific industrial sites could be identified by energy mappings and energy analyses (see also Chapter 3). Based on the findings, individual solutions for heat recovery could be evaluated. The quantification of excess heat on a national or regional level has also great significance. Such analyses help energy planners to include excess heat in their energy system models, policy makers to target the utilisation of excess heat and industries to reconsider their energy use. With this background a large number of European studies were published to quantify the potential of excess heat, in particular of industrial excess heat, and determining its actual utilisation potential.

This chapter presents an overview of the potential amount of excess heat in Denmark. The excess heat potentials were mapped together with the temperature ranges at which the heat was available and the associated exergy content. Two methods were applied to find the excess heat potential. One method is referred to as THERMCYC[1] mapping where the excess heat was determined for all sectors in Denmark and an evaluation of opportunities for solar thermal energy integration was made. Secondly, the industry analysis from the previous chapter was used to quantify industrial excess heat potentials for the analysed sectors. This approach is referred to in the following as process mapping and is the basis for the analyses in Chapter 5. The work presented in this chapter is partly based on [120, 127] ([C1], [T1]).

4.1.1 Definition of excess heat

The heat remaining after an industrial process operation is often referred to as *waste heat*, *surplus heat* or *excess heat*. The term waste heat though implies that heat is unusable or has no value, which is often not the case. The terminology in the following is adopted from the summary by Pettersson and Harvey [128], who gave an overview of the different types of excess heat:

Excess process heat. Heat content of all streams (gas, water, air, etc.) which are discharged from an industrial process at a given moment.

Usable excess heat. The excess heat that it is technically and economically possible to reuse in the industrial process or an external heat sink.

Internally usable excess heat. Excess heat that can be used internally in the process, considering both technical and economic aspects. This usage is normally preferable compared with external usage.

Externally usable excess heat. Excess heat that can be delivered to an external heat sink (e.g. district heating network), considering both technical and economic aspects.

Non-usable excess heat. Remaining part of the excess heat, when the internal and external usable fractions have been deducted. This part can be called waste heat.

If the excess heat is internally usable, the question arises if there is really an excess of heat. Since it could be avoided, the term avoidable excess heat can be used. The opposite would be unavoidable excess heat, i.e. excess heat that cannot be avoided and cannot reduce the use of primary energy at the industrial plant.

An alternative more thermodynamic definition was proposed by Bendig et al. [129]. Also here the authors recommended a better use of the term waste heat, and relate it to the real potential

[1] THERMCYC is a project for the development of advanced thermodynamic cycles utilising low-temperature heat sources for which this mapping was initially performed (Project website: http://www.thermcyc.mek.dtu.dk/).

of extractable work. The difference between avoidable waste heat, which should not be used for a secondary application, as it would block investments into energy efficiency measures, and unavoidable waste heat is pointed out. Waste heat is defined as the sum of the exergy that is available in a process after pinch analysis, heat recovery, process integration and energy conversion (utility) integration with the help of exergy analysis.

4.1.2 Literature review

There are a number of national and regional studies determining the amount of industrial excess heat. One of the early studies was done by Bonilla et al. [130] for the Basque Country in 1997. The waste heat was found by either having general data on the plant or by applying unit operations. The total waste heat was divided by temperature and stream type (gas, solid liquid...) and possible technologies to use these potentials were found.

The analysis by Dupont and Sapora [131] for France targeted the application of heat pumps for excess heat recovery. The study focused on the recoverable heat from air-compressors, cleaning systems and chillers.

Sollesnes and Helgerud [132] found the excess heat potential in Norway by sending questionnaires to 72 industrial firms and evaluating their responses. The majority of the excess heat was found in the wood, pulp and paper industry, followed by the metal and chemical industrial. The data was used to discuss possible utilisation potentials and technologies.

McKenna and Norman [133] categorised heat users in the United Kingdom into broad temperature bands and quantified the heat demand and excess heat at different temperatures for single sites. A method to achieve these goals was further developed which was based on the EU Emissions Trading Scheme and process data. The thermodynamic quality (Carnot-factor) was further used for the assessment. Based on this work, Hammond and Norman [92] analysed the use of the identified recoverable surplus heat. Cooper et al. [134] continued to use the excess heat potentials from the industry to find the potential for its use in district heating networks.

Broberg et al. [135] determined the excess heat potential of industrial sites in Sweden by using questionnaires. The questionnaires were sent to 85 large scale industrial sites in two Swedish regions. Based on the answers the results were extrapolated to represent Sweden as a whole. For one of the regions, Viklund and Johansson [136] performed a more detailed analysis of actual recovery potentials under different energy market scenarios.

Blesl et al. [137] created a method for generating spatial and temporal distributions of heat demands of regions. For the industry the process heating demand is distributed on three temperature levels and by number of employees. The demand for hot water and space heating is further included. Two methods for estimating the heat demand, a rough method only using the type of industry and the number of employees and a more accurate method in which individual process steps and their corresponding mass flow rates are considered. This approach is applied to the region of Baden-Württemberg in Germany. Pehnt et al. [138]

analysed the excess heat potentials in the German industry by applying excess heat factors on the final energy use of the industry sectors in Germany. Only excess heat over 140 °C was mapped and the factors were derived from other studies. In another study [139] the excess heat potential in Germany is found using a bottom-up analysis. Based on defining process energy demands for the different industries and establishing excess heat factors, the amount of excess heat is found by using the total final energy use of the industries with the process data. Brückner [140] and Brückner et al. [141] presented an analysis for the waste heat potential of the German manufacturing industry, further considering the technical and economic boundaries of its utilisation. The mapping was based on the emission data reported by 80,000 companies, which companies are obliged to report every four years in Germany. Based on this data the waste heat potential is found, which was the most detailed analysis for Germany until then. Since the temperatures are based on measurements at the companies, it can be expected that not all excess heat sources are included. Also excess heat sources, which do not contain CO_2 or other critical emissions requiring reporting, might not be included in the reported data. These undocumented sources could be excess heat from cooling or ventilation systems.

For Denmark an investigation by Viegand Maagøe A/S [118] was undertaken to show the waste heat and utilisation potential for several industrial sectors. A questionnaire answered by 25 companies established possible energy savings of 200 GWh per year through internal excess heat utilisation and another 200 GWh per year for district heating supply. The excess heat potential from the industry is further found by applying process conversion efficiencies to the unit operations. Based on the annual energy balances and process energy use in Denmark an excess heat potential of 9 PJ is found across all sectors. This potential was further evaluated with respect to internal recovery, through e.g. heat pumps, and to which degree it is economically accessible.

Other studies quantified potentials on a European level. Naegler et al. [142] determined the process heating demand for the European Union, including the temperature levels. The potentials are found by dividing the total final energy use, first to the final energy use for heat in each industry branch and then to temperature level for each industry branch. This division made with factors established from different German and European data sets. With respect to European waste heat potentials, one of the most cited works is by Persson et al. [143], who used a similar approach to McKenna and Norman [133], converting CO_2-emission data from the European Pollutant Release and Transfer Register (E-PRTR) to find excess heat numbers.

The potential from Persson et al. [143] does not include temperature levels and only the largest emissions, a verification of the potentials is further not found. Brückner et al. [87] reviewed and categorised the methods for finding the industrial waste heat potentials of countries and regions. Based on this work, a detailed overview and discussion of industrial waste heat potentials worldwide was made by Miró et al. [144]. Studies published before 2015 were used and compared. Their work shows how different and often incomparable the studies partly are, as the methodologies, reference years and boundaries are not always reported. Though most studies follow a trend, when comparing the share of excess heat to the total energy use in the industry, some outlier can be found. The industrial waste heat per energy used in the industry was for instance reported as 3 % in Latvia and 4 % in U.S., while it was 56 % in Lithuania and 71 % in Canada. More recently a study by Miró et al. [145] determined the excess heat potential of the European non-metallic industry by using the bottom-up approach from McKenna and Norman [133], which was adapted to use the E-PRTR data.

Miró et al. [146] compared different methods for estimating excess heat potentials, amongst others the one from Persson et al. [143] and [141], and transferred them to the case study of Spain. It is found that these methods, delivering medium precise estimates of excess heat potentials, can be transferred to other regions. The similarity of the initial methods' country to the one it is applied to, however determines if there are additional uncertainties.

The studies found in the literature were either country-specific (e.g. [132, 135, 141]) and thus not applicable to Denmark or did not represent a sufficient level of detail with respect to number of industries, temperature levels and considered processes (e.g. [118, 143, 145]). It was thus necessary to create mapping of excess heat specific to Denmark and taking advantage of the available data and information. The aim was to establish the amounts of excess heat across all sectors in Denmark, while considering the temperatures and origins. The approach and the taken assumptions are described in the following section.

4.2 Methods

The method section is split in two parts, first the method applied as part of an overall mapping of excess heat in Denmark, as developed under the THERMCYC project [120] is introduced (THERMCYC mapping). This is followed by a brief summary of retrieving the excess heat amounts from the energy and exergy analysis of the previous section (Process mapping). The THERMCYC mapping took into account all sectors and the total energy use in Denmark. The process mapping only considered 22 industrial sectors in the Danish manufacturing industry, but with a higher level of detail with respect to temperature levels and number of processes.

4.2.1 THERMCYC mapping

The overall methodology for the assessment of the excess heat potential and its according temperature levels is shown in Figure 4.1. The assessment was based on the energy input to the different sectors which was well documented in the case of Denmark [48]. For all sectors, relevant processes were determined, and, for each sector, the heat containing streams out of the system, as well as the useful share of this excess heat were estimated. Then the temperature of the useful excess heat was assessed. It was assumed that the temperature at which the excess heat is available is the same as the actual process temperature. This means that a process stream was assumed to be available for heat recovery before it enters a cooling tower. For example, a stream leaving of a processing plant requires cooling from 60 °C to 50 °C. This cooling effect is provided by a cooling tower, where air enters at ambient temperature and leaves at 30 °C. In this case the excess heat temperature would be 60 °C to 50 °C.

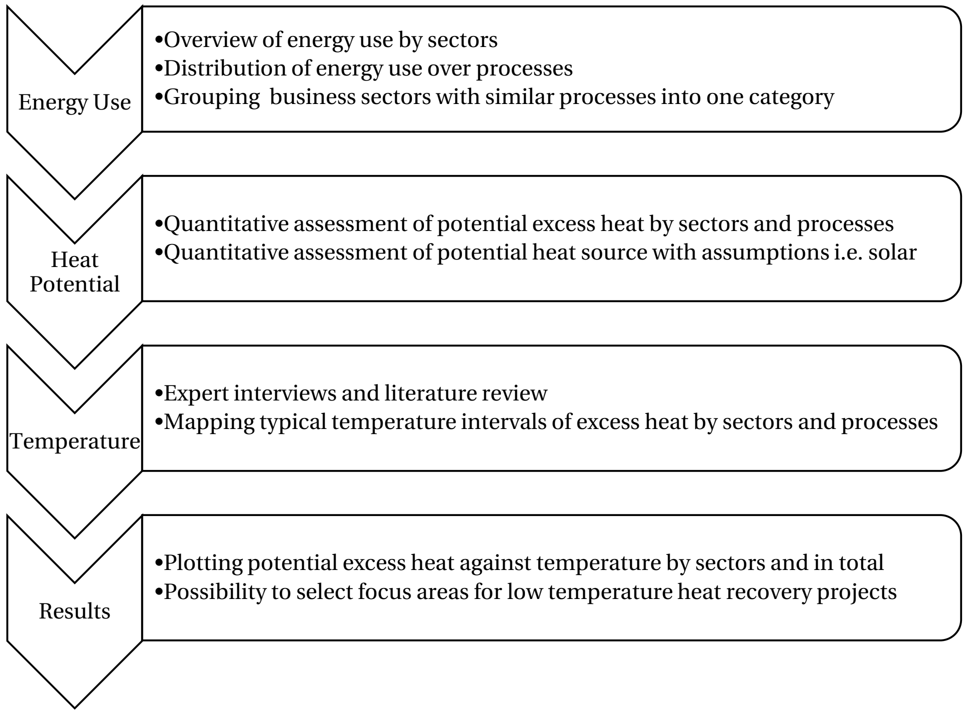


Figure 4.1: Overall methodology for identification of waste heat and potential heat energy.

The evaluation of the accessible excess heat potential and the related temperatures were, for a majority of the cases, based on practical experience with the actual unit of operations in terms of accessibility and temperatures. Furthermore theoretical considerations and inputs from industrial partners, such as AP Møller Mærsk [147], MAN Diesel & Turbo [148] and Danish Technological Institute [149], were used to refine the evaluation and incorporate more units of operation. Besides the energy content and temperature, the medium of the heat sources was given. The heating medium differs from one process to another, and therefore the most common ones are shown.

In the case of solar thermal heat sources, a review of existing literature on their potential in Denmark was carried out in order to assess the suitable areas for utilising solar thermal energy. The potential for solar thermal energy was calculated based on solar thermal collector efficiencies for common collector types at fixed temperatures and suitable areas where collectors could be installed. Solar thermal collectors could supply heat at temperatures up to 75 °C.

Sectors and categories

The main sectors were defined according to the classifications of Statistics Denmark [89], with the exception of trade and transport which were separated into two sectors. An overview of the merged sectors, together with their level one statistical classification of economic activities in the European Community (NACE) [90] can be found in Appendix A.1. The given sectors were merged into eight categories, based on similarities of the energy consuming processes within the sectors. The subsequent categories were industry, buildings, utility services, construction, transport including maritime and the three natural categories, solar, geothermal and air/water.

The industry category consisted of manufacturing, agriculture, forestry, fishing, trade and mining. In the building category several sectors were merged as they had similar energy consumption patterns. This included, amongst others the sectors households, information and communication, financial and insurance and public administration. Within the utility services the supply of electricity, natural gas, district heating and water were included. For each of these services the relevant processes were found. For example the supply of electricity was divided into steam power plants, gas turbines, combined cycles and combustion engines.

The construction category used mainly thermal energy for heating and drying [150]. However the excess heat is primarily generated in temporary installations on construction sites. It was therefore difficult to control the flow of excess heat and to distinguish between energy use on fixed and temporary installations. For these reasons and due to a lack of data in this category, this was not further evaluated. The transport category summarised activities related to passenger and freight transport and associated businesses and facilities. In this category the main focus was on road transport by truck and maritime shipping.

Assumptions

The mapping of the excess heat from the industry sector was primarily based on reports from the Danish Energy Agency (Energistyrelsen) [111, 151] and expert consultations. In this category secondary heat, from e.g. ventilation, lighting, and vehicle transport were neglected, as they only provide a small quantity of the total energy input to this sector.

Within the utility services the accessible waste heat for each service was analysed based on the production units [151]. The supply of gas and fresh water was neglected as there were no significant heat sources in their supply chain. For the generation of electricity, steam and hot water, the majority of the waste heat was found in flue gases and water in condensers, for which the temperature and still usable waste heat amount was found [126, 152]. Another important sector in this category was the treatment of waste water [153], where waste heat was available from the treated water [154], biogas production and drying and disposal of sludge.

In this analysis the focus in the transport sector lied on shipping and road transport by truck. For both transport modes the main processes, where waste heat was found, were charge air, engine cooling and energy in the exhaust gases. In case of maritime transport the amounts of useable waste heat and temperature ranges were based on information from MAN Diesel & Turbo [148] and Maersk [147]. The analysis of road transportation was based on transportation by truck where the fuel distribution [155] and temperatures [156] were taken into account.

The excess heat in the building category was found as the heat loss from the boilers for hot water and space heating, refrigeration, cooling, IT, electronics and electrical equipment. Though space heating itself could account for up to 70 % of the fuel and 80 % of the district heat use, it was evaluated that there was no accessible excess heat potential. This was based on the assumption that all new buildings were equipped with heat recovery systems and a majority of aged buildings were naturally ventilated.

The assessment of the solar thermal potential in Denmark was based on suitable areas and technologies to harvest the solar irradiance. Areas suitable for the installation of solar thermal collectors were divided into residential, agricultural, industrial, commercial and public. The suitable area for the first four sections was only for installations on buildings [157], where the suitable area was defined as an area with a minimum annual irradiance of 80 % of the country's maximum. The public sector was assumed to primarily consist of open land, where solar installations could provide district heating [158]. For each sector an applicable solar collector type was selected based on the required temperature range [159]. The conversion efficiency of the solar collector was then found as a function of the collector type and temperature using the ScenoCalc, a solar collector energy output calculator [160]. For residential and public installation standard flat plate collectors were chosen and evacuated tube collectors for agricultural, industrial and commercial installations. The achievable temperatures depend to a high degree on the collector technologies, which is in practice decided by economic factors and application area. Assuming an average ambient temperature of 15 °C, a solar collector efficiency of 28 % was retrieved for evacuated tube collectors, delivering heat at 100 °C. For flat plate collectors, an efficiency of up to 40 % at a delivery temperature of 70 °C was used.

Exergy

In addition to the energy content and temperature of the excess heat, exergy was also used as an indicator to quantify and assess the value of the heat sources. In this analysis exergy was a particular interesting indicator as it quantifies the usefulness of the low temperature heat, mainly for power production, but also for heat pumps which utilise two exergy sources – power and low temperature heat. The exergy calculations were simplified and the following assumptions were made.

Only physical exergy, at an atmospheric pressure, was used in this work. All other exergy contributions, such as chemical, kinetic and potential exergy, were neglected. The temperature of the media was taken as the average of the estimated temperature interval. The reference state was defined at atmospheric pressure and a temperature of 15 °C. It was further assumed that liquids and gases could be cooled down in practice to the reference temperature and 40 °C respectively. All liquids were treated as water and all gases were treated as air.

4.2.2 Process mapping

The model developed and data used in Chapter 3 were used to map excess heat and process heating demands from the respective industry sectors. In contrary to the THERMCYC mapping, only 22 industries and only thermal processes were considered. The 22 industries are stated in Table 3.2 and with their NACE classification in Table A.2. All industries were part of the NACE level one classification 'C Manufacturing', except gravel and stone (sector 15) which was part of classification B. This limited the total number of processes and industries to analyse and allowed for a more detailed analysis of the excess heat streams and temperature. Based on the energy conversion efficiencies from the previous chapter, the amount of heat losses from each processes was known and temperatures for these streams were assigned. As for the process heat, also here up to three temperatures were defined per process. These temperatures represent an average excess heat temperature which was assessed to be commonly found in such industrial processes, when no waste heat recovery system is installed.

4.2.3 Indicators for excess heat comparison

As the two approaches described above were based on different assumptions and system boundaries, it was necessary to define some indicators to assess the results. This was also necessary in order to compare different studies and sectors.

A comparison of the estimated excess heat per amount of energy included in the mapping was performed for the two mappings. This comparison was done once using the total energy input as the denominator and once only including the energy used for processes. A similar comparison was performed for other studies on a sector level. Here the comparison was done by dividing the excess heat found in one sector with the total energy input to this sector in the reference year.

4.3 Results

In this section, first the excess heat potential following the THERMCYC mapping will be presented, followed by the one from the process. At the end, the results of the two methods will be combined and compared to other studies.

4.3.1 THERMCYC Mapping

In the following the excess heat and exergy potential of the sectors analysed as part of the THERMCYC mapping are shown, together with the temperature ranges for the relevant processes in each category. The total potential for heat recovery was found to be 212 PJ per year which correspond to 13 % of the net energy input for end users and producers. The large potential was within the transport (36 %), secondly within utility (28 %), industry (23 %) and buildings (11 %).

In the industry the majority of the accessible excess heat in the industry sector was available from evaporation and refrigeration operations. As can be seen in Figure 4.2, also boiler losses and drying processes presented a recovery potential, as here a high exergy content was found. Evaporation processes were primarily found in the oil extraction and refinery processes, where the heat was available in a temperature interval of 35 °C to 50 °C. The excess heat from boilers, furnaces and melting processes was available at high temperatures, which makes these processes interesting to focus on. This was also expressed in the available exergy, which had a potential of 1.4 PJ equivalent to 25 % of the total exergy potential in the industry.

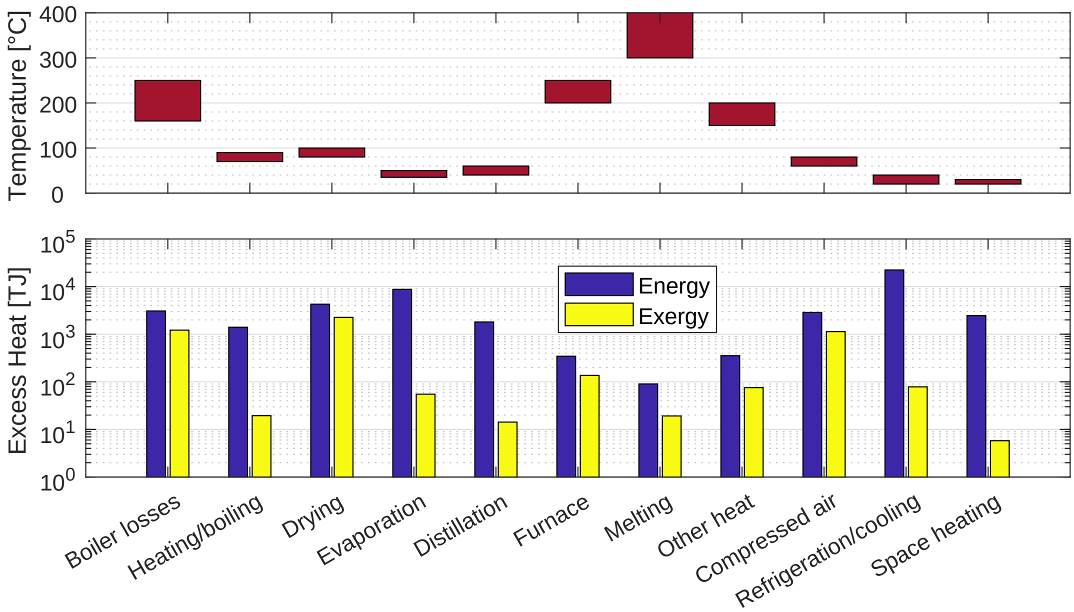


Figure 4.2: Excess heat from the industry by processes and with typical temperature ranges.

The next graph (Figure 4.3) shows the excess heat from the utility sector. The highest potential of excess heat originated from steam power plants, which were a common pant type within the Danish utility system. The low temperature of the condensate (typically below 20 °C) resulted in a small exergy content, in contrary to the flue gases where temperatures of up to 180 °C were found. In large power plants it is practical to keep the stack temperature at around 180 °C in order to avoid acid formation and to ensure proper dispersion of the flue gases from the stack to the atmosphere [126]. In practice it can therefore be challenging to utilise this excess heat source.

Figure 4.4 shows the results of the excess heat mapping for the building category. In this category all temperatures are below 100 °C. The highest potential originated from refrigeration and cooling, where almost 20 PJ were available. However the exergy content was relatively small due to the low temperatures in these processes.

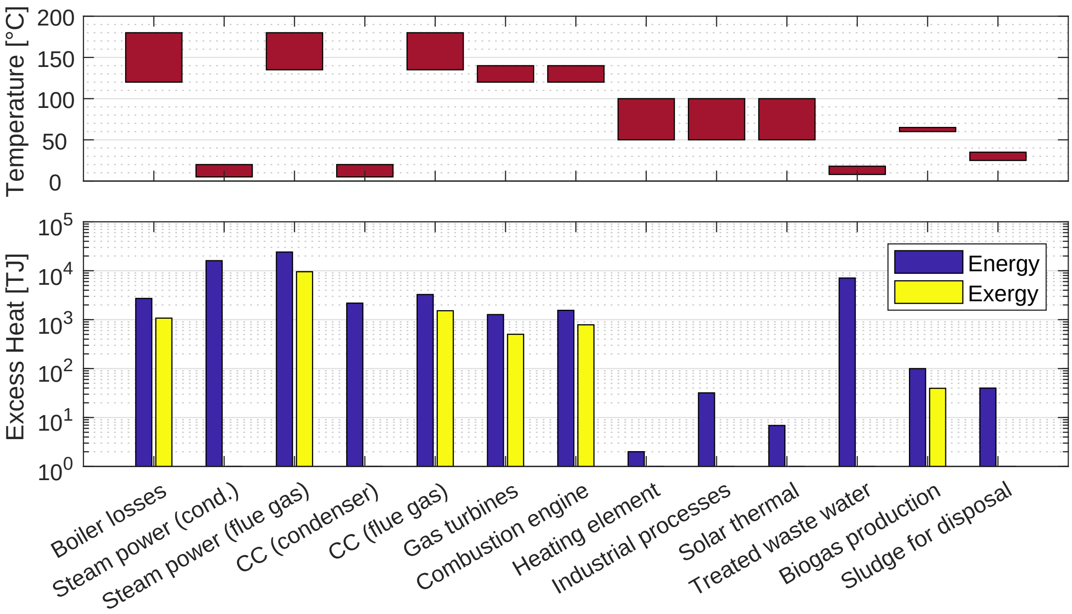


Figure 4.3: Excess heat from the utility sector by processes and with typical temperature ranges.

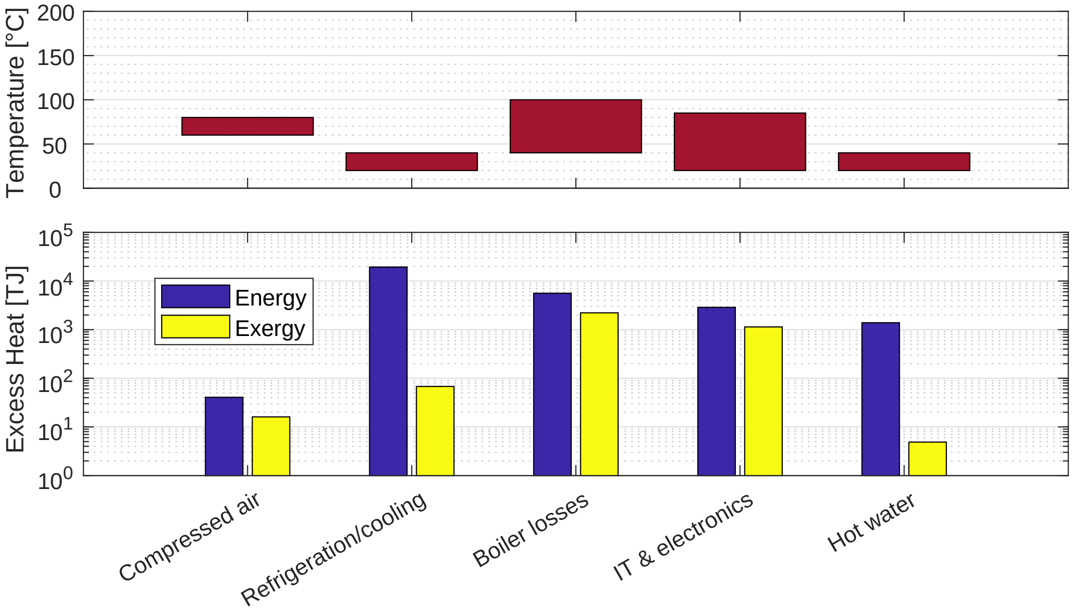


Figure 4.4: Excess heat from the building sector by processes and with typical temperature ranges.

The transport sector (Figure 4.5) had a large potential for further use of the excess heat. The highest potential was found in the exhaust gases of the shipping sector, where also high temperatures of up to 400 °C were present. Also for road transport by truck a large potential with high temperatures was available in the exhaust gases. The influence of these high temperatures on the exergy content was also noticeable. The charge air cooling had a larger excess heat potential and a higher temperature range than the engine cooling. However the medium of engine cooling was water instead of gases, which could be more easily exploited in limited space.

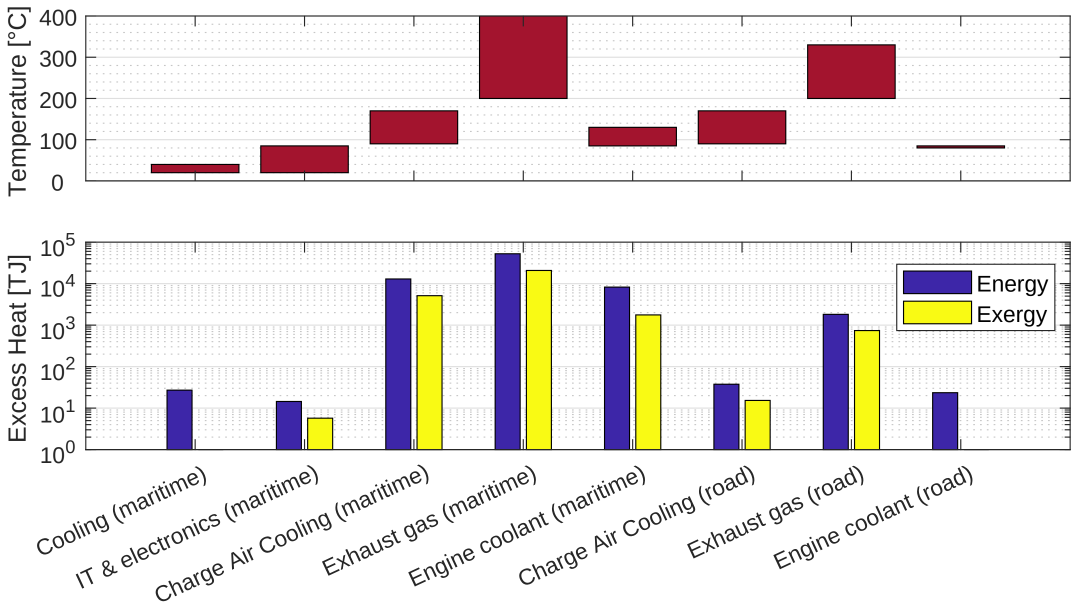


Figure 4.5: Excess heat from the transport sector by processes and with typical temperature ranges.

At the end an evaluation for the solar thermal potential was performed. This potential was by far the highest in the public sector with 380 PJ, due to the large areas found there. Because temperatures of below 75 °C were assumed for installations in the public sector, the largest solar thermal potential lied below this temperature. However temperatures of up to 100 °C are possible by using, for example, evacuated tube collectors, but this would reduce the accessible amount of heat. The solar heating potential in the residential sector was found to be 92 PJ, the potential of the industry to be 14 PJ and of the commercial sector 22 PJ.

4.3.2 Process mapping

The results for the excess potential by industry sector and temperature, as found based on the data of the industry analysis described in the previous chapter are presented in Figure 4.6. It can be seen that the results were dominated by low temperature excess heat from oil refineries and high temperature excess heat from the building material (cement and bricks) production. The medium temperature excess heat between 80 °C and 180 °C was distributed across most sectors. It has to be noted though that a considerable part of the excess heat between 140 °C to 180 °C and 220 °C to 260 °C was from boiler losses (exhaust gases). This potential is not fully technical recoverable. A total excess heat potential of 12.7 PJ was found.

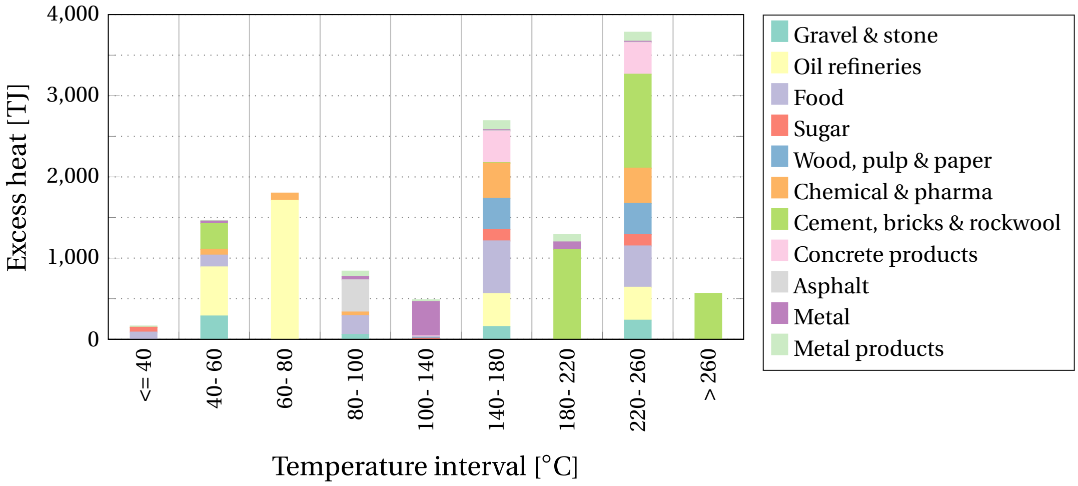


Figure 4.6: Excess heat from thermal processes by temperature level for 11 types of manufacturing industries in Denmark.

4.3.3 Overall mapping

Based on the THERMCYC mapping, the total excess heat potential including solar thermal energy was found to be 736 PJ per year. Out of this potential, 85 % were available below 100 °C. Not including solar energy, the sectors in Denmark had a total excess heat potential of 212 PJ of which only 49 % of the heat was found at temperatures below 100 °C.

In terms of exergy a total potential of 126 PJ was found of which 74 PJ originated from solar irradiation. In contrast to energy, only 17 % of the exergy, when excluding solar thermal, originate from excess heat at temperatures below 100 °C. With solar thermal energy the exergy potential originating from heat at 100 °C is 66 %. A large exergy potential was further found for excess heat at temperatures between 130 °C and 175 °C, where 25 % of the total exergy originated from, resulting primarily from the utility and transport sector.

On a sectoral level the largest potentials were found for the transport sector (75 PJ), utility sector (58 PJ) and industry sector (48 PJ). Within the industry sector, the manufacturing industry accounted for almost 23 PJ of excess heat.

When analysing the sources of the waste heat, the highest potentials were found in the exhaust gases of the transport sector where 26 % of the total heat was found. This source was followed by refrigeration and cooling (20 %), flue gas from steam power plants (11 %) and condensate from power plants (8 %).

In terms of exergy, the largest potential was also found in the exhaust gases of the transport sector, representing more than 40 % of the total exergy, followed by flue gases from steam power plants. Boiler losses in the industry and buildings had the third largest exergy potential with a share of almost 9 %, while they only accounted for 5 % of the excess heat.

In Figure 4.7 the excess heat from the mining and manufacturing industry found in the THERMCYC mapping and from the thermal processes in the manufacturing industry found based on the exergy analysis were compared. The excess heat form thermal processes was roughly one third of the total possible mapped excess heat. However, while 95 % of the total potential was below 100 °C, it was only for 65 % of the excess heat from thermal processes.

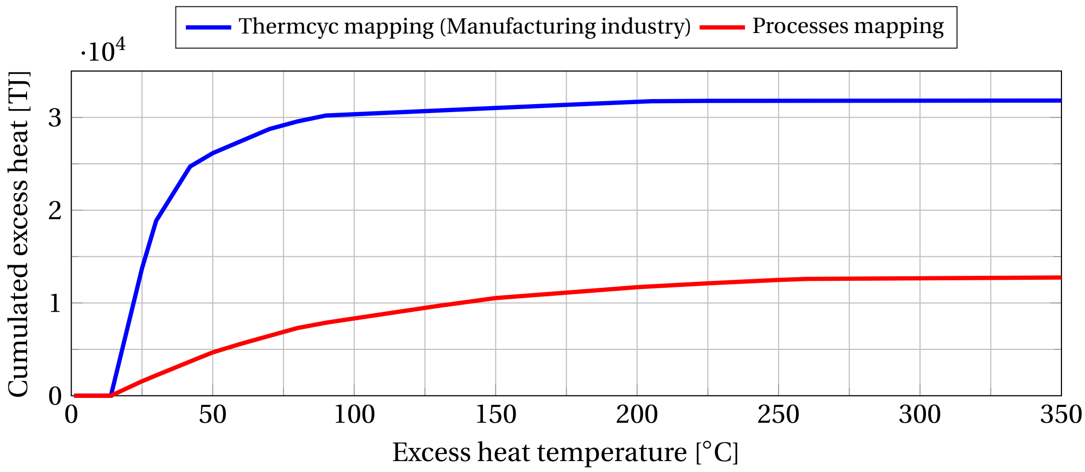


Figure 4.7: Cumulated excess heat potential for manufacturing industry in Denmark based on the analyses for 2012.

4.3.4 Comparison

A number of differences across the available studies made a comparison of the excess heat amounts difficult. The scope of the analyses varied considerably, meaning the considered industrial sectors, excess heat sources (gaseous, high temperature etc.) and the potential (technical, physical etc.) are not consistent. Furthermore the reported reference year and reference temperatures are not uniform. Due to the lack of excess heat estimates for Denmark a sufficient comparison was difficult to obtain.

Three studies reporting excess heat amounts for Denmark were identified. The one by Persson et al. [143] found 12 PJ of excess heat a year, but only considered eight excess heat emitters in Denmark. This corresponds to 11 % of the total 2012 energy use in the Danish industry.

Miró et al. [144] reported 13 PJ of excess heat based on the study from Persson et al. [143]. Most recently, Miró et al. [145] found between 0.9 PJ and 1.7 PJ of EH from the non-metallic mineral industry in Denmark for the year 2012. In practice this excess heat is credited to one company (cement production) in Denmark and represented between 4.1 % and 7.8 % of the total industry energy use in 2012. The estimate by Viegand Maagøe A/S [118], also for the reference year 2012, found a total excess heat potential of 50 PJ for the industry sector in Denmark. The manufacturing industry had a share of 56 % in this potential. The majority originated from cooling operation and 6 PJ from processes.

The current work found, using the THERMCYC approach, an EH potential of 20.1 PJ and 12.6 PJ using the exergy analysis for the manufacturing industry as shown in Table 4.1. The THERMCYC study considered all industrial sectors and all the energy used in the industry, while the approach described in the previous chapter only considered 22 industries and only excess heat from thermal processes. Therefore the share of the excess heat from the total energy use was lower. The fraction of excess heat from processes to the energy use for these processes was also slightly lower for the excess heat based on the exergy analysis. Miró et al. [144] gave an overview of national studies, comparing the fraction of excess heat per total energy use, which this work estimated between 14.8 % and 18.5 %. For Sweden these numbers were between 5.5 % and 18.4 %, for Germany 18.8 % and 20.7 %, United Kingdom 5.5 % and 21.3 % and France 19.8 % and 26.0 %. The higher values in these ranges generally originated from the study by Persson et al. [143].

Table 4.1: Summary of energy use and excess heat amounts found in this work for Denmark in 2012 (excluding space heating).

		THERMCYC	Process mapping
Total industry energy use	[PJ]	108.70	108.70
Industry energy use included in mapping	[PJ]	108.70	85.25
Process energy use included in mapping	[PJ]	88.40	60.25
Excess heat from processes	[PJ]	20.12	12.63
Excess heat per total industry energy use	[%]	18.5%	11.6%
Excess heat per process energy use	[%]	22.8%	21.0%

A comparison of the excess heat per total energy use of a specific industry sector is more difficult. Though many studies used the NACE classification [90], not all processes and production units were included or are the same. The structure of the national industries were also very different, making a comparison of e.g. the German chemical industry to the Danish one difficult. A comparison of excess heat factors is shown in Table 4.2, which can also be seen as a very rough indication for the range of possible values. Brückner [140] abstained from having direct comparison of this data, as the background of these numbers was too different. The comparison here is thus only intended to show the possible range of values. It can be seen that the THERMCYC estimates had partly an opposite trend to the other studies. The sectors metal and non-metal materials had the lowest amounts of excess heat per energy used, while the food and chemical had the highest. These differences may result from the approach used in the THERMCYC method, which focused on low-temperature heat sources, generally neglected in other works. The excess heat potentials found through the exergy analysis had in general the same trend as the other studies, though they were a bit overestimated compared to the study of Brückner [140] and underestimated to the study of Sollesnes and Helgerud [132], which are seen as the most comprehensive ones.

Comparing the THERMCYC and process mapping, both performed in this work, the main difference was found for the excess heat factors of metal and non-metal minerals. These considerable lower numbers found for the THERMCYC mapping were primarily based on the assumption that already 90 % of the excess heat from furnaces and melting were already utilised. This also means that the THERMCYC mapping was considerably more sensitive to single assumptions, as they were taken for a process category and are applied to all industries.

Table 4.2: Excess heat factor (excess heat divided by energy use) from different studies for various sectors.

	Denmark THERMCYC	Denmark Process	Norway[1] [132]	Germany[2] [138]	Germany[3] [140]	EU[4] [143]
Food	0.39	0.18	0.15	-	0.1	0.1
Wood & Pulp and Paper	0.19	0.17	0.44	-	0.09- 0.1	0.25
Chemical	0.28	0.19	1.57[5]	0.08	0.09	0.25
Plastic & Rubber	0.19	0.24	-	0.03	0.17	-
Non-metal minerals	0.03	0.25	0.46	0.4	0.15	0.25
Metal	0.05	0.29	0.58	0.3	0.19	0.25

[1] Reference temperature 0 °C.
[2] Reference temperature 20 °C and only excess heat above 140 °C.
[3] Reference temperature 35 °C.
[4] No reference temperature given.
[5] Exothermic reactions were included in this analysis.

THERMCYC Mapping The accessible excess heat, found with the THERMCYC mapping, of 212 PJ in the analysed Danish sectors corresponded to 13 % of the energy used by the utility and end use sectors. The total energy consumption of 1650 PJ estimated in this study included producers where an energy conversion takes place (production of heat and power) and therefore some of the energy input was accounted for twice. The Danish net energy input was with 791 PJ in 2012 [151] significantly lower than the energy use applied in the present analysis, as the net energy input only used primary energy and did not include the energy for maritime shipping.

The large potential of excess heat below 50 °C makes the use of e.g. heat pumps necessary if process integration is targeted. The feasibility of recovering the low temperature heat sources also depends on the potential users and their location and temporal variations in relation to the source. As Denmark has a large district heating network, many sources in most of the sectors, could be used to supply heat to the network. This is presented in Chapter 5. In the shipping sector excess heat could be used to generate power to replace commonly used diesel generators. However for each source an individual and detailed analysis has to be undertaken to locate and assess possible users of the recovered heat.

The simplifications, assumptions and sectoral calculations cause uncertainties of the quantified exess heat amounts in this analysis. However the aim of this work was to identify processes and sectors which are suitable to analyse further with respect to new technologies being developed. These technologies will still be viable, even if the total potential in a sector is lower in reality, as the first targets are the more easily accessible sources.

In the shipping sector 16 % of the energy used was available as excess heat, and most of this heat had high temperature levels. The excess heat in the industry sector was available at lower temperatures, however the unused and accessible excess heat represented more than 18 % of the total energy input.

Industry sector The focus of this work was the industry and thus the process mapping was used to obtain a more detailed excess heat potential of the industrial sectors. The two mappings were meant to complement each other and are based on the same data sets [48, 88]. A high level of detail was obtained in the process mapping, as each unit operation was evaluated individually for each industry sector.

On assumption in this work was that only the sensible heat of the excess heat sources was considered. A large fraction of the excess heat sources in the form of flue gases and drying air will have a water content, which could condensate. This heat of condensation could be substantial, but was not considered in this work. The main reason for this was the assumption that condensation is undesirable due to corrosive components in the flue gases which could harm materials. This is rather a technical challenge and can be circumvented in many cases.

4.4 Conclusion

The THERMCYC mapping of the available excess heat in Denmark was based on the energy use in five Danish sectors. The largest potential for excess heat was within the transport sector, where a total of 76 PJ were estimated as recoverable excess heat. The second largest potential was found with more than 58 PJ in the utility sector, followed by the industry and building sectors where the potentials are 48 PJ and 25 PJ, respectively. The results show that despite great efforts in industrial energy efficiency, a large potential in optimising processes and reusing excess heat still exists. It is expected that large quantities of the excess heat could be reused within the industrial sectors. Considering the accessible excess heat from all sectors, there are two major potentials. First, low temperature waste heat in the form of water from cooling/refrigeration, condensate and various industrial processes all below 60 °C. Secondly there is high temperature waste heat in the form of exhaust gas from various combustion and heating processes. The large amount of low temperature excess heat calls for innovative methods to utilise these sources. For temperatures below 60 °C heat pumps could be used to upgrade the excess heat or it could be directly used in ultra-low temperature district heating. For higher temperatures, power cycles like the organic Rankine cycle and the Kalina cycle can be used to utilise the heat for production of electrical power.

As part of the process mapping, the excess heat from thermal processes in the manufacturing industry was analysed in more detail. Low temperature excess heat (less than 60 °C) was quantified with approximately 1.5 PJ and originated from refineries, building material, food and chemical industries. A large potential was found between 140 °C and 180 °C, as well as 220 °C and 260 °C, which originated from exhaust gases (e.g. boilers) and can only be partly recovered.

5 Utilisation potential of industrial excess heat for district heating

In this chapter a spatial, temporal, thermodynamic and economic analysis of industrial excess heat and district heat in Denmark is performed. The method, applicable to other regions, is described first for the spatial distribution of industrial excess heat and thermodynamic recovery potential. The found theoretical maximum potential for supplying district heat with industrial excess heat is then refined and evaluated in a second step. This is done by including the time profiles of heat sources and sinks and by considering economic factors.

5.1 Introduction

District heating has played an important role in the Danish energy past and it can be expected that it will be important in the future as well. After the first oil crisis in 1973, district heating based on Combined Heat and Power (CHP) plants was one of the instant measures to fight the crisis and increase the overall system efficiency. In 1972 75 % of the heating demand in Denmark was supplied through the combustion of oil [161]. Over the last four decades, the share of District Heating (DH) for domestic heating in the country grew from 20 % in 1972 to 50 % in 2016 [161], thus becoming the dominant means of supply and replacing oil fired heaters to share of less than 6 %. Around 63 % of the citizens in Denmark are connected to district heating networks [162]. In the same period the share of CHP plants in the district heating production increased from 28 % to 67 %, while the share of renewable energy in DH (including biomass for CHP) grew from close to 0 % to up to 48 %. In order to reduce the environmental impact of district heating (DH) in Denmark, the share of renewable DH based on solar energy and biomass was increased steadily over the last two decades according to the national energy statistics [8]. The share of excess heat utilised for the supply of DH in 2015 was 2 % [114].

The long term goal in the Danish society is to become 100 % renewable in all sectors of the energy system before 2050 [163, 164]. To reach this goal stronger efforts have to be undertaken to replace fossil and environmentally harmful energy sources. The increased utilisation of excess heat for district heating purposes could be a part of the solution. However, many reports and energy scenarios do not analyse the role of industrial excess heat for district heating or do not emphasise it, but only agree that DH should be expanded in the future to cover a higher share of the heat demand.

5.1.1 Literature review

Münster et al. [165] analysed three scenarios for the Danish energy system in 2025 and concluded that district heating should be expanded to cover between 55 % and 57 % of the heating demand. Different mixes of fuels and technologies are found to be optimal in different scenarios, but industrial excess heat was not a part of the mix in any of the scenarios. Lund et al. [166] analysed a future 100 % renewable Danish energy system. Their analysis shows that it would be optimal to expand district heating to between 63 % and 70 % of the future heating demand. Even though excess heat is mentioned as a way to reduce fuel input and district heating is emphasised as a crucial medium for utilisation of excess heat, the role of excess heat was not analysed in more detail. Möller and Lund [167] investigated the expansion of district heating into natural gas areas and recommended to expand district heating to cover between 50 % and 70 % of the future heating demand. They have assumed that excess heat can cover between 83 GWh and 153 GWh of the net heating demand each year; this assumption is not elaborated further.

Mathiesen et al. [168] proposed a vision of a 100 % renewable Danish energy system in 2050 including a description of intermediate scenarios for 2015 and 2030. The proposed solution includes a drastic expansion of district heating networks until 2030. As a result, heat supply from district heating remains constant until 2050 despite significant heat savings. District heating is produced from biomass, solar heating, electric boilers and large-scale heat pumps, while industrial excess heat was not considered as an alternative. The limitation of biomass use for heating in a 100 % renewable energy system was analysed by Mathiesen et al. [169]. Industrial surplus heat of 2.65 TWh per year was included in the study and the results showed that it is economically feasible. It is also stated that district heating is important in 100 % renewable energy systems as it allows the utilisation of, for instance, large-scale solar thermal plants, large-scale heat pumps and industrial surplus heat.

To find the optimal heat supply for a housing community from the energy system perspective, Karlsson et al. [170] used the TIMES-DK model. District heating proved to be optimal from the system perspective in all analysed scenarios. In the scenario leading to a 100 % renewable energy system before 2050, surplus heat from biorefineries contributed to district heating production in central[1] areas of East Denmark with around 4.2 TWh per year after 2035. These biorefineries represent investments calculated by the model and do not currently exist in

[1] In the Energy Producers Count by the Danish Energy Agency [171] district heating producers are grouped into central and decentral. Central and decentral plants supply central and decentral DH areas, respectively. The central DH areas have higher heating demands, installed capacities and transmission efficiencies compared to decentral DH areas.

Denmark. In the analysis of energy scenarios up to 2020, 2035 and 2050 published by the Danish Energy Agency [172] industrial excess heat contributed to the production of DH with annually 0.89 TWh and 0.42 TWh in central and decentral DH areas, respectively. Despite the existing and possible future potential of excess heat contributing to the supply of district heat, only a few works have thoroughly studied it. From the studies [166, 167, 169, 170, 172] it can be further concluded that industrial excess heat brings socio-economic benefits, improves energy system efficiency and reduces primary energy demands. Since these benefits are generally desired, utilisation of EH for DH could also be interesting in countries and regions outside of Denmark.

Several studies aimed at quantifying industrial Excess Heat (EH), also referred to as waste heat, and their theoretical utilisation potential, as well as the appropriate technologies. The study by Miró et al. [144] quantified the excess heat for different countries and regions. On the European level, Naegler et al. [142] quantified the industrial heat demand by branch and temperature level. This work provides useful information for further analyses of EH in Europe. The methods used to estimate the excess heat potential of regions, were categorised and reviewed by Brückner et al. [87]. The geographical locations of the heat sources were not specifically taken into account, however size parameters for companies (e.g. number of employees) were used in the classification. Brückner et al. [173] further investigated the utilisation of EH for residential heating in an urban neighbourhood. The potential for heating and cooling applications was studied in particular, as well as the feasible investment costs for different technologies and consumers. Electric heat pumps were found to be profitable for all consumers, when operating hours exceeded 4000 hours per year. The authors concluded that the heating demand of the area cannot be covered by EH sources within its border. Excess heat should however still be accounted for when refurbishing buildings.

For Sweden, Broberg et al. [135] estimated the industrial excess heat potential for district heating networks and showed how EH investments could become profitable. An economic analysis was performed for this purpose for five cases and different scenarios with respect to the future value of the EH. A positive net present value was obtained in almost all cases and scenarios over a conservative 20 year lifetime Viklund and Johansson [136] reviewed the technologies for the utilisation of EH and estimated their potential for a region in Sweden. The results showed that a high potential was found for DH, considering only heat sources above 95 °C and no heat pumps. An analysis by Hammond and Norman [92] showed the heat recovery opportunities in the UK industry. The authors estimated the potential of excess heat from 11 industrial sectors and, based on the excess heat temperatures, showed the utilisation potential for different technologies. In addition, an analysis of heat transportation between sites with surplus heat and heating demand was performed. Another study for the UK [134] investigated the potential of using industrial excess heat for district heating. An assessment of the potential based on transmission distances was performed and it was found that approximately one third of the UK excess heat could be used for DH. A relevant study for the present work was performed by McKenna and Norman [133], where a spatial model of industrial heat loads and technical recovery potentials in the UK were presented. This study analysed heat loads and EH, grouping them into different temperature bands and estimating the recovery potential. The distribution of the heat was done mainly by site allocation based on the EU Emission Trading Scheme (ETS). The results show the geographical distribution of needed and rejected heat by industrial sector and temperature interval.

Aydemir et al. [174] considered heat integration between companies, for which a method and spatial model for determining heating demands at industry locations was developed. Weinberger et al. [175] analysed different configuration for cooperation between EH and DH in a Swedish DH network, from economic and environmental perspectives. Their study shows that it is a benefit for the DH system to integrate an extended EH supply to the DH network. Karner et al. [176, 177] considered multiple case studies in Austria, where synergies between industries and urban areas were possible. The synergies included amongst others the utilisation of waste heat for heating, cooling or electricity generation.

Persson et al. [143] presented a methodology to assess annual excess heat volumes from fuel combustion activities in energy and industrial facilities based on CO_2 emission data from the E-PRTR. This study was performed on the EU level. Their results show that the theoretical excess heat from industrial facilities in Denmark amounts to 3.4 TWh per year. This potential includes some excess heat from thermal heat and power production as well as high-temperature sources. Since that analysis does not cover small-scale industrial facilities, they claim that 12.4 PJ (3.4 TWh) represents a conservative estimate of the maximum annual excess heat potential. It is also stated that excess heat temperature levels and state of matter, variations of excess heat over a year as well as site-specific factors greatly influence the realisable potentials. However, these factors were not taken into account in [143]. The present study comes a step closer to the realisable potential by taking into account temperature levels of excess heat and the medium containing the excess heat. A study by Lund and Persson [178] maps potential heat sources for district heating in Denmark, which could be exploited by using heat pumps. Even though they have focused on low-temperature sources, the theoretical (maximum) industrial excess heat potential of 3.4 TWh per year is inherited from Persson et al. [143]. It is claimed that surplus heat from the industry is probably the most feasible out of all excess heat sources and it will probably be utilised before ambient heat sources. Even though they have focused on low-temperature sources, the theoretical maximum industrial excess heat potential found by Persson et al. [143] was used, not performing an individual assessment. The sub-annual temporal distribution and temperature levels of industrial EH were not considered in these studies.

Even though several studies [133, 134, 143, 178] focused on industrial excess heat utilisation using spatial models, it is necessary to include temperature levels of EH and district heating networks as well as detailed geographical and temporal analyses of sources and sinks to bring the theoretical potentials closer to the realisable ones. Other studies [135, 173] considered the economic feasibility, but did not take overall and sectoral potentials into account. It is further necessary to assess the socio-economic costs of excess heat utilisation on a national level in order to determine not only the technical, but also the economic potential. Several barriers were identified with respect to the utilisation of EH for DH. The location of the sources and lack of infrastructure were identified as particularly important [179]. In addition a lack of knowledge of possible EH consumers and about available EH were identified by Viklund [180]. The authors suggested that future work should analyse the potentials and tools, which promote heat collaborations on a regional level.

5.1.2 Aim and approach

The aim of this chapter is to develop a new method for determining national and regional potentials for utilising industrial excess heat for the heating of buildings with district heat. It is based on the papers [181, 182] ([P3],[P4]).

This is done by first introducing and validating a novel approach to geographically distribute industrial excess heat to single production units. Secondly, spatial analyses in GIS (Geographic Information System) are performed to link the excess heat sources with the specific district heating networks. As a result, the present study gets a step closer to a realistic potential than what was found in the previous work. As for the mapped industrial processes and district heating areas temperature levels were included, the potential and performance of heat pumps could be further found.

Based on this spatial and thermodynamic analysis, an assessment of the suitability of EH from specific industries for district heating and of the costs for using EH for DH was performed. To do so, the temporal patterns of heat demand and EH availability were included, to allow the analysis of required heat storages and temporal mismatches. Then an economic analysis was performed based on investment and O&M costs of the heat recovery equipment. By taking these parameters into account it was possible to conduct detailed analyses of heat synergies between industries and heating areas. Among others, these analyses included the need for thermal storages, obtainable district heating costs and preferable industries. The main aims of this chapter are defined as follows:

(i) Geographically represent industrial excess heat and district heating areas, which allows energy planners to identify potential synergies between industrial excess heat and district heating.

(ii) Present a methodology for the analysis of excess heat sources and district heating.

(iii) Show how future changes at the industrial sites, district heat consumers and heat distribution can affect the potential of EH for DH.

(iv) Determine the potential for the utilisation of excess heat for district heating purposes in Denmark and differentiate the potential coverable directly or via heat pumps.

(v) Presentation of a methodology for the analysis of the utilisation of industrial EH for district heating, including thermodynamic, spatial, temporal and economic parameters

(vi) Creation of hourly profiles for EH availability and DH demand

(vii) Assessment and comparison of industrial groups towards their suitability of being used for district heat.

(viii) Analysis of socio-economic heating costs of the utilised industrial EH

The present chapter is structured as follows. First the method is introduced in Section 5.2, where the proposed methodology for describing the distribution of the excess heat, quantification of DH demands and linking of EH sources and DH demands performed in GIS is explained. The thermodynamic analysis for heat pumps and direct heat transfer are presented afterwards, followed by the temporal profiles, cost estimation procedure and modelling of the thermal storage. The results are then presented in Section 5.3. First the outcome of the spatial and thermodynamic analysis is shown in Section 5.3.1, followed by refined potential using temporal profiles and costs (Section 5.3.2), and a sensitivity analysis on the relevant parameters (Section 5.3.3). At the end, the validity of the methodology and results are discussed and conclusions are drawn.

5.2 Methods

In the following the lied and developed methods for the determination and quantification of EH potentials for DH are explained. The overall modelling structure, as well as the overall elements of the method are schematically shown in Figure 5.1. Each model element (from spatial to economic) is based on the preceding one, all having the excess heat and heating demands as common input. The first results were obtained, after the thermodynamic model, where the main outcome was the theoretical potential for EH to DH. These results were then further refined and analysed by adding the temporal profiles and economic data. For each model evaluation a sensitivity analysis was performed.

5.2.1 Spatial and thermodynamic analysis of excess heat

The first two parts of the modelling structure (Figure 5.1) are presented in the following. First, the approach for determining the EH at specific production units, as well as the technical recovery is presented. In the second part, spatially detailed linking of EH sources and DH demands are presented.

Industry analysis

The aim of this section is to present a method to determine industrial excess heat on a sectoral level and distribute these sources to all relevant locations where production units are found. Furthermore, the temperature levels of the EH at each unit are to be determined, to allow the assessment of its utilisation potential. To account for the reduction of excess heat due to energy efficiency measures on site and the use of EH for DH, an assessment of the theoretical avoidable excess heat was performed.

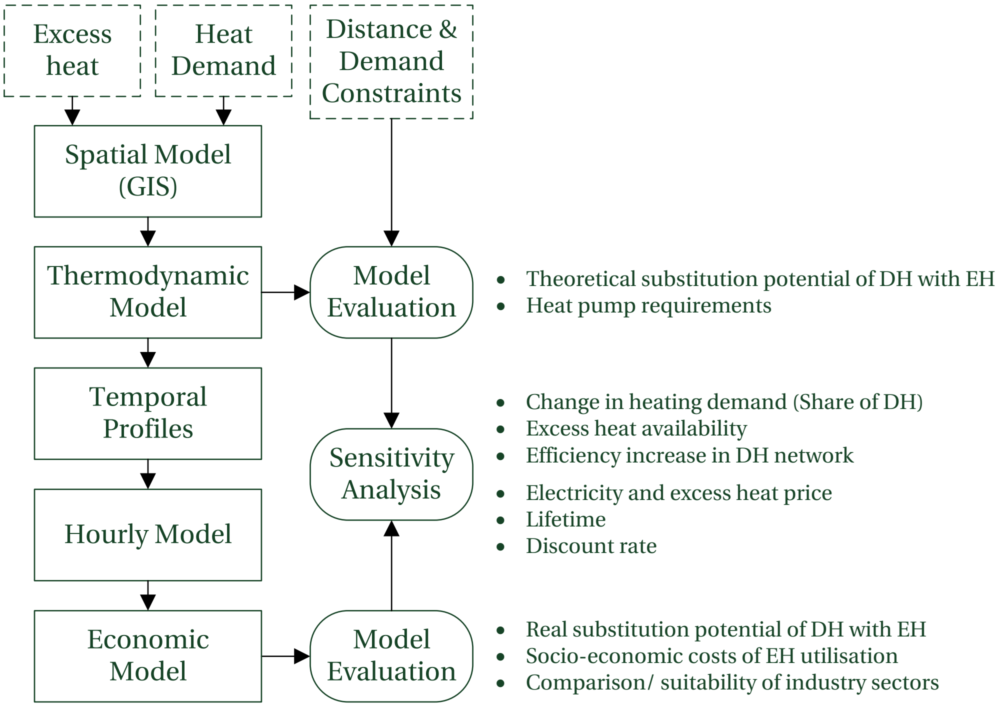


Figure 5.1: Elements and modelling structure of the industrial excess heat and district heating analysis.

Industrial excess heat Chapter 3 described the energy end-use models for 22 manufacturing industries, which were used in Chapter 4 (Studies: [91, 127]) to quantify the annual excess heat and temperature levels in Denmark. The following analysis is based on these industries and the excess heat from the thermal processes. The spatial analysis of EH relies on this quantification and distribution, as well as on industrial process information gathered. An overview of the 22 industrial sectors and their energy use and excess heat can be found in Table 5.1 for the reference year 2012 based on [48, 91, 114]. The table has the same data background as Table 3.2 presented in Section 3.3. The total fuel and electricity for thermal processes are used to determine the given excess heat amounts. The amounts of CO_2 emitted by these processes are used to allocate excess heat to the production sites. The refining of oil and production of building materials represented the sectors with the largest fuel use and consequently with the highest excess heat potentials in 2012. Furthermore, these high potentials were distributed to only a few production sites in Denmark. The majority of production sites were found in the metal, food and chemical industries.

Excess heat location The locations of the units were available from the Central Company Register (CVR). For the chosen industry sectors 2573 production sites were established. The allocation of EH to the single production units was performed in multiple steps to account for

Table 5.1: Overview of the data used and calculated excess heat for the 22 industrial sectors for the year 2012.

	Industrial Sector	**Total Fuel** [GWh/yr]	**Process Electricity** [GWh/yr]	**Excess Heat**[a] [GWh/yr]	**CO_2 Emissions**[a] [kton/yr]	**Sites** [-]
1	Gravel and stones	834	93	204	101	137
2	Oil Refineries	4,513	298	871	1,019	5
3	Meat	591	483	108	106	81
4	Dairy	1,060	508	189	188	73
5	Compound feed	361	215	43	66	70
6	Sugar	826	103	95	226	2
7	Other food	495	316	85	109	144
8	Wood	888	217	148	17	235
9	Pulp & Paper	550	170	46	87	114
10	Industrial Gasses	14	113	0	0	19
11	Enzymes	214	249	53	42	9
12	Other chemicals	161	228	24	31	14
13	Pharmaceuticals	359	401	69	84	97
14	Plastic and rubber	218	516	40	17	356
15	Paint & Soap	895	318	91	184	38
16	Cement	2,575	303	668	881	2
17	Bricks	367	34	78	70	19
18	Asphalt	430	34	114	84	50
19	Rockwool	473	95	126	143	17
20	Concrete & other	811	83	121	161	103
21	Production of Metal	451	369	169	84	42
22	Metal working	691	486	83	50	946

[a] Thermal process related.

the different levels of information available for the individual sites. First detailed information from energy mappings was used to assign EH amounts to production units if available. The use of actual energy use data or excess heat amounts obtained from site specific analyses has the highest accuracy. This information was very limited and was used for a validation of the distribution presented in Section 5.4. The second allocation step was based on CO_2 emissions of production units, documented as part of the E-PRTR, to allocate EH. The total CO_2 emissions of each sector were found using the total primary energy input and the specific CO_2 emissions of the fuels. The total CO_2 emissions and the CO_2 emissions of the production units were directly correlated to the excess heat amounts. Approximately 90 production units were covered using this allocation in Denmark. The E-PRTR data may for some units also contain process related CO_2 emissions, for example from the calcination of limestone in the cement production. These emissions have to be subtracted if the production units grouped in one industry sector have different amounts of process related CO_2 emissions per unit of energy used.

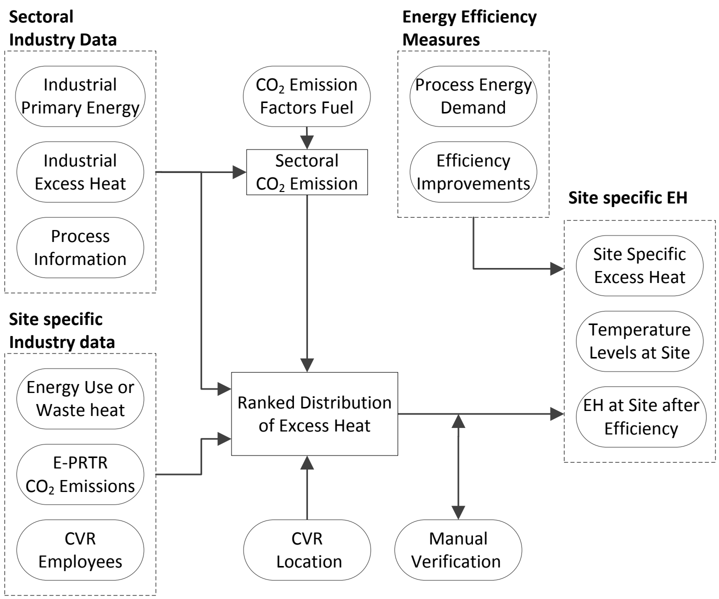


Figure 5.2: Methodology for the determination of excess heat, temperature levels and avoidable excess heat.

The third allocation step was applied to the majority of the production units with small to medium sizes. This step was performed based on the number of employees registered in the CVR database. The main industrial sectors were divided into sub-sectors and excess heat was distributed amongst them. This step allocated EH to the majority of the units, which represent, though, only 35 % of the total excess heat. Lastly, for sites where none of the above information was available, a manual check was performed to guarantee that important production units were not discarded.

In Figure 5.2 the distribution is graphically presented. The inclusion of energy efficiency measures is also shown, as explained in Section 5.2.1. For this analysis, the required input is on one hand industry data for processes, energy use and excess heat on a sector level. On the other hand, site specific data is required, such as energy use, CO_2 emissions and employees. Sectoral data is available for most countries in varying detail, whereby the used site specific data is available for most European countries. The results of the distribution are the EH amounts and EH temperature levels at each production unit in the country. Furthermore EH amounts after possible energy efficiency measures are obtained.

Utilisation of excess heat The utilisation of the EH for district heating depends on the excess heat temperature and temperature profile of the respective network. The excess heat was divided into two temperature ranges.

(i) Excess heat below 60 °C which uses water as carrier

(ii) Excess heat above 60 °C which uses gas as carrier

For the utilisation the minimum temperature difference, ΔT_{min}, was chosen to be 10 K for gases (e.g. flue gases, drying air) as carrying medium of the excess heat and 5 K for liquids (e.g. condensate). It was assumed that gases may be cooled down to 40 °C, to account for undesirable condensation and minimum stack temperatures. Liquids may be cooled down to the average environmental condition which was set to be 15 °C.

It was further distinguished if the excess heat source can be utilised directly for district heating or if a heat pump is necessary. A combination of direct heat transfer and heat pump could increase the system efficiency, but such a possibility was not considered in this work. The method is described in Section 2.4.

Energy efficiency measures in the industry To quantify the impact of the future energy efficiency measures in the industry on the EH and thus on the potential for DH, a sensitivity analysis was performed. Kromann et al. [84] estimated the energy efficiency potential for most industries in Denmark. All industry sectors, except oil refineries were included, for which a specific analysis was performed using data from similar processes.

The energy efficiency measures were assumed to be directly correlated to excess heat amounts and to cover all thermal processes. Each measure was described by the energy savings when implementing the measure in a process and by the potential for applying this measure to the whole industry (applicability). Table 5.2 gives an overview of the considered energy efficiency measures for the main process categories. The weighted average energy savings, by which the process energy use was reduced, are given together with the lowest and highest values (stated in the brackets in Table 5.2) applied to the different industries. The applicability states the fraction of processes for which the energy savings were possible. Thus, the total energy savings for a specific process in a given industry were found by multiplying these two values. The chosen values reflect the energy saving potential obtainable in the medium potential scenario with short payback periods.

Spatial analysis

The present work investigates which part of the available excess heat can be fed into the DH networks and consequently supply buildings with heat. This section analyses two factors that can limit the use of EH for DH. First, the installation of a DH network will be limited by the amount of EH and the distance between the EH source and DH demand. For example,

Table 5.2: Overview of energy efficiency measures for different processes, average energy savings and applicability to the sectors.

Process	**Possible Measures**	**Energy Savings** [%]	**Applicability** [%]
Evaporation	Heat pump, Adaptive control	48 (20- 90)	26 (3- 50)
Heating	Heat pump, Reduction of temperatures, Overall measures	32 (8- 55)	27 (8- 75)
Drying	Vacuum drying, Infrared drying, Steam Drying, Advanced process control	24 (10- 60)	20 (8- 50)
Total site	Process integration, Internal use of excess heat	6	82
Utility	Humidification of combustion air	8	5

the transmission of heat from a small supermarket over 10 km is technically possible but the installation of a DH network is probably not economically feasible. A maximal distance between EH source and DH areas is introduced to account for this limitation. Secondly, the entire excess heat potential cannot be utilised if the amount of EH from an industrial facility minus the transmission and distribution losses is larger than the heating demand in a DH area. For example, a large steel factory could supply all buildings within a town. However, if there is no city or a larger town in its vicinity, then it is not possible to utilise the entire excess heat potential.

GIS tools incorporated in ArcGIS 10.4 [183] were applied to find the total heating demand which can be covered by excess heat from industrial facilities. The applied procedure to find this potential was as follows:

1. Excess heat sources (Section 5.2.1) and official district heating areas [184] were projected on top of a background map in ArcGIS 10.4. Annual district heating statistics published by the Danish District Heating Association [185] were used to assign average annual efficiencies and seasonal supply and return temperatures to district heating areas.

2. The BBR database[2] with all buildings presented as points were projected on top of the previous layers. This layer contains information about the buildings' heated area, use, construction year and type of heating installations (district heating, natural gas boiler, etc.). The specific heating demand (in kWh per m^2 and year) were assigned to each building based on the construction period and use [186]. The annual heating demands of buildings were calculated as a product of its heated area and specific heating demand. Information about the type of heating installations were used to classify buildings into "DH buildings" and "Not DH buildings".

3. For each excess heat source, the nearest DH area was identified. It is assumed that the

[2] BBR (in Danish "Bygnings- og Boligregistret") is an acronym for the Danish Register of Buildings and Dwellings.

excess heat is delivered to the nearest DH area.

4. If an industrial excess heat source was located outside of a DH area, the cut-off distance was identified, i.e. the maximum allowed distance from excess heat source to the nearest DH area. This evaluation took into account a maximum connection costs per MWh of heat delivered and the costs for transmission pipes as a function of the capacity [187]. The allowed connection costs were set to 4.17 Euro per MWh per year delivered to the district heating network. This value reflects the cut-off criteria and was chosen based on expected expansion costs of DH areas [188]. Heat sources located within existing DH areas were assumed to be always connectible.
   Figure 5.3a shows the cut-off distance of the excess heat sources as a function of the EH size. Figure 5.3b shows the amount of industrial production sites within given excess heat intervals. For example, there are approximately 200 production units with EH sizes between 200 MWh per year and 400 MWh per year, for which a maximum distance of around 150 m is found. The majority of the EH sources have to be within a close distance (less than 200 meters) to be considered. For some of the largest excess heat emitters, larger distances of above 1000 meters were feasible.

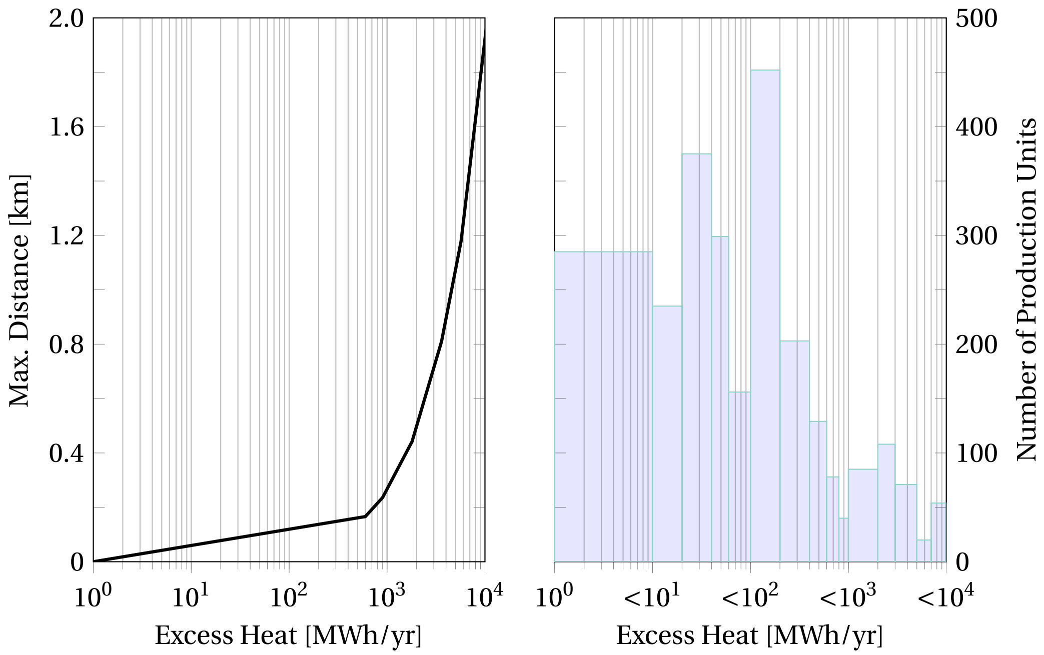
5. If the EH source could be connected to a DH area, respecting the criteria from point 4, the deliverable excess heat amount was reduced for transmission and distribution losses. If no DH area fulfilled the criteria from point 4, the excess heat was not considered.

6. For each DH area, the following quantities were summarised:

   - HD_{DH} - Heating demand of "DH buildings"
   - $HD_{not\ DH}$ - Heating demand of "Not DH buildings"
   - EH_{DIR} - Heating demand which could be supplied directly from industrial excess heat (without heat pumps)
   - EH_{HP} - Heating demand which could be supplied from industrial excess heat with heat pumps and
   - Electricity needed to run heat pumps.

7. For each DH area, HD_{DH}, EH_{DIR} and EH_{HP} (calculated in step 6) were compared:

   - If $HD_{DH} < EH_{DIR}$, then $EH_{DIR} = HD_{DH}$, while $EH_{HP} = 0$. In this case, a part of the potential for direct use and none of the potential for use of industrial excess heat with heat pumps could be utilised for district heating.
   - If $EH_{DIR} < HD_{DH} < EH_{DIR} + EH_{HP}$, then EH_{DIR} remains the same while $EH_{HP} = HD_{DH} - EH_{DIR}$. In this case, a full potential for direct use and a part of the potential for use of industrial excess heat with heat pumps could be utilised.
   - If $HD_{DH} > EH_{DIR} + EH_{HP}$, EH_{DIR} and EH_{HP} remain unchanged. In this case, entire industrial excess heat potential could be utilised for district heating.



(a) Cut-off distance as a function of EH

(b) Histogram of units per EH interval

Figure 5.3: Cut-off distance as a function of the excess heat amount and number of production units within given annual excess heat intervals presented as histogram.

5.2.2 Temporal and economic analysis of excess heat

The second part of the method described in the following takes the spatial and thermodynamic analysis from Section 5.2.1 as the point of departure, which included two constrained factors for the utilisation of EH for DH - the cut-off distance and the lack of demand. The cut-off distance refers to maximum allowed distance between EH source, while the lack of demand refers to the cases in which EH from an industrial facility minus the transmission and distribution losses is larger than the heating demand in a DH area. The lack of demand is included in the following. The DH costs were calculated instead of limiting the potentials with the cut-off distance. Therefore, the procedure was further developed. As in the previous analysis, the heating demand of buildings supplied by DH was summarized to get the heating demand which could be supplied from industrial EH (directly or through a heat pump). However now only buildings supplied by DH were considered as a prospective heating demand. Figure 5.4 shows the main system elements and pathways considered in this work. Each industrial site can have multiple EH sources at different temperatures, which are used directly or through a thermal energy storage (TES) depending on the temporal profiles. A heat pump or a heat exchanger are used if the temperatures of the source and sink require it. Based on the geographic location (within or outside of DH areas), transmission pipes for the delivery of DH could be required.

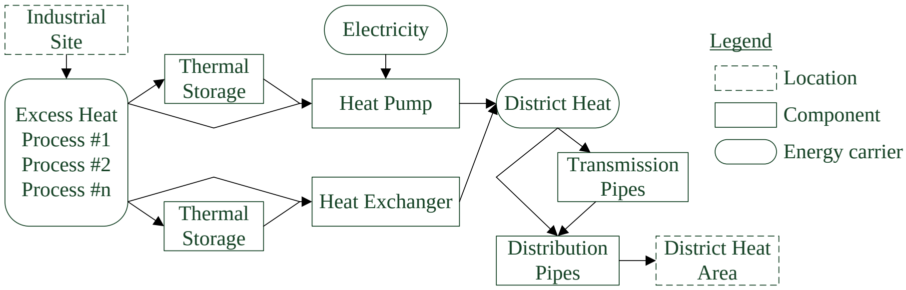


Figure 5.4: Principle conversion pathways of industrial excess heat to district heat with components and their placement considered in this work.

Temporal analysis

The temporal variations of heat demand and excess heat availability were included in the present analysis to assess the temporal mismatches between supply and demand, the sizes of required thermal storages and the capacity of the components (heat pumps, heat exchangers and district heating pipes). The temporal variations of heat demands and EH have both an impact on the economic performance and the utilisation potential. As the district heating demands[3] and industrial EH sources vary over a day, week and season, the temporal profiles used in this analysis have an hourly resolution over a year. The profiles with hourly resolution were created based on one representative week (Monday to Sunday) for each season (winter, spring, summer and autumn). A detailed description of the method and the profiles is given in the following.

Industry This work considers 22 industries which can be divided into 43 sub-sectors. Based on similarities in the production processes of the sub-sectors, the industrial sectors were grouped into 11 categories (see Appendix A.2). The majority of the manufacturing industries can be described by production occurring in either one, two or three shifts. An additional load profile for one shift was used, when a base load exists. In addition, seasonal variations were included for industries, if applicable. Scheduled production stops, due to e.g. holidays or for maintenance, were not included.

To account for the relation between company size and production profile, the number of employees at each production site was used to determine the number of shifts for some industry categories. An overview of the categories and their profiles is given in Table 5.3. If more than one shift is given in the table, the company size was used to determine the number of shifts. The arrows further indicate if the production is higher or lower during certain seasons. The extent and quantification of seasonal distribution are presented in Appendix A.4. This quantification is specific to Denmark and the load profiles available for the reference year. The

[3] If not specified otherwise, heating demand is the sum of demand for space heating and domestic hot water.

seasonal variation of the cement production for example could be greater, but was chosen constant due to a lack of data for the single site in Denmark. The development of the profiles

Table 5.3: Description of the temporal patterns for each industry category.

Industry category	Week	Seasonal variation
Gravel & stone	1 Shift	Winter ↑↑
Oil refineries	3 Shift	None
Food	1/2/3 Shifts	None
Sugar	2 Shifts	Autumn & Winter ↑↑
Wood, pulp & paper	1/2/3 Shifts	None
Chemical & pharmaceutical	1/2/3 Shifts	Winter ↑
Cement, bricks & rockwool	1/2/3 Shifts	None
Concrete products	1 Shift (base load)	Winter ↑
Asphalt	2 Shift	Winter ↓↓
Metal	3 Shift	None
Metalproducts	1/2/3 Shifts	None

was based on industrial experience, available process information and data from the industry. Wiese and Baldini [189] created load profiles based on hourly natural gas consumption data over one year in Denmark, which were also available for a total of 17 subsectors used in this work. Each dataset was built of up to 6 production sites and was used to validate and refine the created profiles. The representative load profiles for 1, 2 and 3 shifts, as well as 1 shift with base load are shown in Figure 5.5. Each profile shown in the figure, distributes the weekly energy use on the hours of one week.

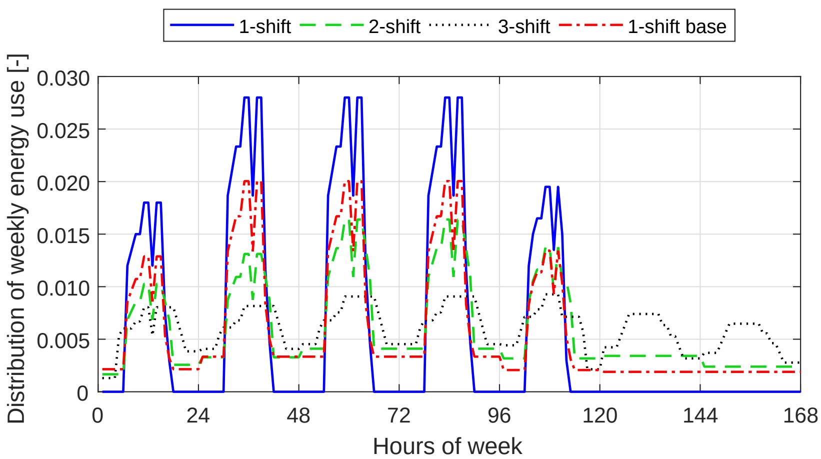


Figure 5.5: Industrial load profiles for thermal processes based on the number of shifts at the industrial site.

Heating demand of district heating areas For every district heating area, the annual heating demands of buildings (aggregated) are calculated as described in Section 5.2.1. The distribution of the annual heating demand over one year followed two steps. First, the buildings were aggregated into four groups according to common use - residential, office & service, culture & public or leisure. The aggregation of 21 building uses into 4 is adapted from the BBR and presented in Appendix A.3. Second, the heating demand was divided into demand for space heating and domestic hot water (DHW). The share of DHW demand on the annual level was assumed to be 21 % for residential and leisure buildings and 10 % for office & service and culture & public [190]. Different hourly demand patterns were assumed for weekdays and weekend for each building groups. Around 80 % of the DHW demand was distributed to follow the daily living activities and is independent of the outside air temperature. It was further assumed that the DHW demand is constant over the seasons. The remaining 20 % were uniformly distributed to the remaining hours. This was done to replicate the diversity within building groups. For example, even though most of the people sleep during night, some consumers require DHW in that period.

The space heating demand constitutes the remaining part of heating demand. Space heating demand depends on the heat loss through the elements of the buildings envelope, i.e. on the outside temperature. The outside temperatures are obtained from the Design Reference Year (DRY) dataset [191]. To illustrate how the aggregated heat demand profiles look, an example for the Ringkøbing DH network is shown in Figure 5.6. This network is constituted of 70 % residential, 20 % office & service, 8 % culture & public and 2 % leisure users. This example shows the distribution of annual heating demand over one week for each season. The artificially created heating demands were compared to samples from the actual heat load delivered to the DH network. Examples are shown in Appendix A.5 for a weekday and weekend in each season. All days were chosen as the third Monday of the first month of each season. In addition the data is compared on an annual level. The artificial profiles approximate the real ones and the seasons are in the same order of magnitude. The DH demand in the summer seems to be underestimated in the created profiles for the reference years and the specific case.

Economic analysis

The economic analysis included the cost of equipment necessary to recover and transfer EH to DH areas. Investments in district heating pipelines were only needed if the EH source was located outside of existing DH areas. If the EH temperature was high enough to be used directly, heat pumps were not needed and only investments in heat exchanger installations should be made. Otherwise, an investment in heat pumps was necessary. In the cases where there is a temporal mismatch between excess heat production and district heating demand, a thermal storage was needed additionally. This is also visualised in Figure 5.4. The investment costs of heat exchangers, heat pumps, pipes and thermal storages were assumed to depend on their required size to reflect the economy of scale, as described in more detail in Subsection 5.2.2.

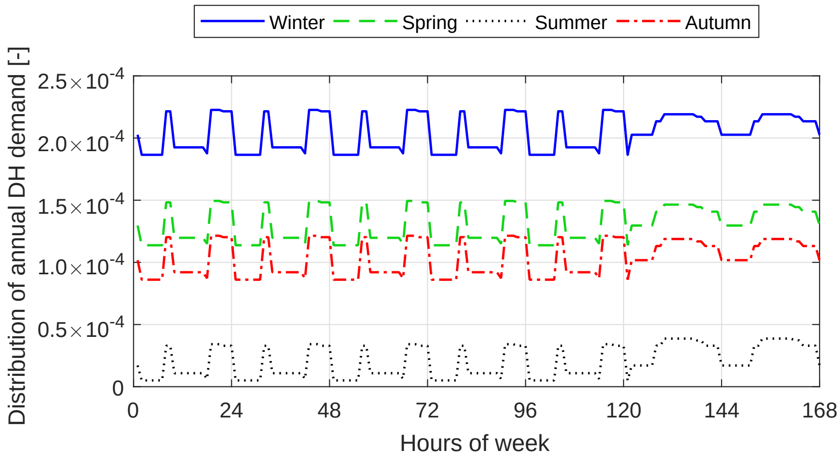


Figure 5.6: Annual distribution of DH demand in Ringkøbing, shown for one week in each season.

For each match between EH source and DH area, an economic evaluation was performed. This evaluation was based on simplified socio-economic principles, which excluded e.g. energy taxes and value added taxes. However, this analysis did not consider all externalities included in a socio-economic analysis, such as health and environmental effects. The aim was to determine the unit costs of the heat supplied and thus to be able to benchmark EH to other heat sources, as well as to analyse and compare the distribution of costs between industrial sectors. The economic analysis was based on the investment costs, I, and the annual fixed and variable Operation & Maintenance (O&M) costs, $C_{f,\mathrm{OM}}$ and $C_{v,\mathrm{OM}}$. Investment costs were found for each match and include the DH pipes, heat exchangers, heat pumps and TES. For the operation of the system the electricity prices for heat pumps were used, together with maintenance costs for HP and heat exchangers as described in the following chapter. The evaluation was done using the unit costs of supplied heat, c_H, as shown in Section 2.6.

A loan duration was chosen to be equal to the lifetime of the equipment (20 years), with a socio-economic interest rate i of 4 % [192]. All prices for equipment were adjusted to the reference year 2016 using the Chemical engineering plant cost index [193].

Cost estimation

DH pipes The costs for DH pipes were taken from Nielsen and Müller [187], where the investment costs per meter of pipe were available for transmission capacities between 0.2 MW and 190 MW. Capacities in between the ones given were found by linear interpolation and capacities outside are found by extrapolating using the Piecewise Cubic Hermite Interpolating Polynomial [194].

Heat exchanger The investment costs for heat exchangers, used for the direct heat transfer from the EH source to the district heating network, $\dot{Q}_H$, were estimated based on the required heat transfer area A_{HEX}. Using Eq. 5.1, the required area of the heat exchanger can be found. The logarithmic mean of the temperature difference in counter-current heat exchanger, LMTD, was found for each match and EH temperature level. The DH supply and return temperature were known together with the ones of the EH source. It was assumed that the EH is rejected to the environment at a temperature of 10 K above the DH return temperature. The overall heat transfer coefficient, k, is chosen for shell-and-tube heat exchanger, with gas at atmospheric pressure on the tube side and water on the shell side [195]. In this work it was set to 60 $\mathrm{Wm^{-2}K^{-1}}$.

$$\dot{Q}_H = k\, A_{\mathrm{HEX}}\, \mathrm{LMTD} \tag{5.1}$$

For heat transfer areas below 80 $\mathrm{m^2}$ the cost correlation established by Ommen et al. [196] and for areas above 80 $\mathrm{m^2}$ the one presented in Andreasen et al. [197] were used. Only fixed O&M costs were used for heat exchangers. These were set to 5000 € $\mathrm{MW^{-1}}$ $\mathrm{year^{-1}}$ [198].

Heat pump The investment costs, economic and thermodynamic performance of the heat pump depend on many factors, such as the sink and source temperature, the temperature increase on the sink side, working fluid and compressor type [199, 200]. To avoid the sizing of heat pump components for each match and temperature level, an approach relying on existing heat pump systems was chosen. The investment costs and operating conditions of 17 heat pumps utilizing EH between 25 °C and 50 °C, and delivering heat between 70 °C and 85 ° were collected. This data was used to create a cost function for heat pumps. Because the found heat pumps had relatively high heating capacities (above 420 kW), 12 additional ground water and air heat pumps with lower capacities were included. The information about the heat pumps were available from previous projects and from the Danish Energy Agency [201, 202].

From the fitted curves (Fig. 5.7), two cost functions were determined and used for the cost estimations. For heating capacities below 1.5 MW the fit function in Eq. 5.2 based on all heat pumps (Fit All) was used. For heat pumps with a higher capacity the fit function in Eq. 5.3 for was used based on the fit *EH HP*.

These cost functions were also in accordance with the recommendation by the Danish Energy Agency [201], that for large heat deliveries, several heat pumps connected in series or parallel are used instead of increasing the size of the components. This typically leads to a cost increase between 70 % and 90 % for each doubling in capacity. Wolf et al. [203] analysed the costs for heat pumps from 8 manufacturers in the capacity range from 4.7 kW to 183 kW. For water-to-water heat pumps the cost curves show similar specific investment costs for very small sizes, however the decrease in costs is a lot stronger. Compared to Wolf et al. [203] the cost functions used in this chapter, the investment costs are overestimated, however standard HP were used

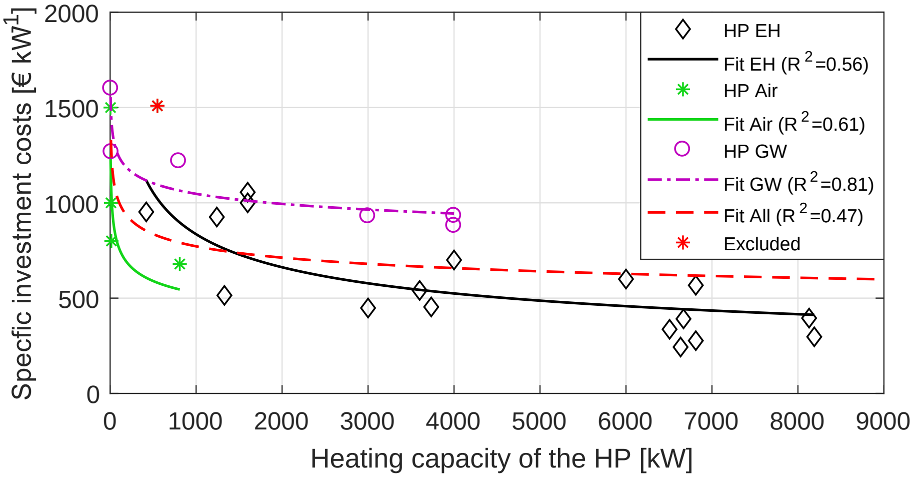


Figure 5.7: Analysis of the heat pump solutions.

and units above 183 kW are said to be custom built.

$$c_{\mathrm{HP}} = 1716 \cdot \dot{Q}_H^{-0.12} \tag{5.2}$$

$$c_{\mathrm{HP}} = 8493 \cdot \dot{Q}_H^{-0.33} \tag{5.3}$$

The O&M costs for the heat pumps were estimated to be 2000 € MW^{-1} year^{-1} for fixed O&M and 2 € MWh^{-1} year^{-1} for variable O&M [202]. In addition, a net electricity price of 57 € MWh^{-1} and annual electricity price increases of 3.5 % were used [204].

Thermal energy storage The costs of the thermal energy storage were found based on the volume of water which has to be stored. Three cost correlations were used to account for the different storage types. Vessels were used for volumes below 150 m^3, tanks below 5000 m^3 and closed water pits for all other volumes. The required volume was based on the required energy to be saved and the temperature difference of the supply and return line of the given DH area. The cost equation is shown in Eq. 5.4, where the total cost C_{TES} for the storage K depends on the reference storage size $V_{\mathrm{TES,ref}}$, total reference costs $C_{\mathrm{TES,ref}}$ and the scaling exponent γ. The reference values used are listed in Table 5.4. O&M costs were only included for storage tanks above 5000 m^3 and were 0.7 % of the investment costs as recommended by the Danish Energy Agency [188].

$$C_{\mathrm{TES},k} = C_{\mathrm{TES,ref}} \left(\frac{V_{\mathrm{TES},k}}{V_{\mathrm{TES,ref}}} \right)^{\gamma} \tag{5.4}$$

Table 5.4: Data used for the investment cost estimation for TES.

V_{TES} [m^3]	$C_{TES,ref}$ [€]	γ [-]	$V_{TES,ref}$ [m^3]	Year [-]	Source
< 150	10,000	0.65	10	2001	[21, 205]
< 5000	348,000	0.55	4000	2006	[21, 206]
> 5000	600,000	0.70	10000	2006	[21, 206]

Case evaluation

The spatial and thermodynamic operations described in Section 5.2.1 result in the maximum transferable amount of EH from each industrial site to the nearest DH area by direct heat transfer and through HPs. Using the temporal profiles established in Section 5.2.2 the total annual EH, Q_{EH}, for each industrial site p was distributed over the year as shown in Eq. 5.5. This is done by multiplying the hourly distribution, $P_{EH,t,p}$, with the annual EH amount. The total annual DH demand, Q_{DH}, was distributed over the hours of the year for each respective share of DH user, S_{DH}, using Eq. 5.6. This was done for each DH area q and type of DH use, r, as described in Section 5.2.2. The procedure is similar to the one for EH, using $P_{DH,t,r}$ of the HD distribution.

$$Q_{EH,t,p} = Q_{EH,p} \cdot P_{EH,t,p}, \text{with} \sum_{t=1}^{8736} P_{EH,t,p} = 1 \tag{5.5}$$

$$Q_{DH,t,q} = \sum_{r=1}^{4} S_{DH,r,q} \cdot Q_{DH,q} \cdot P_{DH,t,r}, \text{with} \sum_{r=1}^{4} \sum_{t=1}^{8736} P_{DH,t,r} = 1 \tag{5.6}$$

This distribution resulted in 2854 hourly time series for EH and 438 for the HD in each DH area. For each industrial site and its nearest DH area, a comparison of the hourly profiles was made, to find the direct EH utilisation and the requirement for TES. For each hour of the year, the share of DH coverable by (i) EH through direct heat exchange, (ii) EH through HP and (iii) EH from the TES was found. If the EH exceeded the HD during one hour t, the heat was added to the TES and was available for use from the next hour $t+1$. EH from direct heat exchange was prioritised to the one from HP and TES. Furthermore, it was distinguished between storing EH requiring a HP and EH for direct heat transfer, as also shown in Fig. 5.4. If the TES had heat left at the end of the year ($t = 8736$), this heat was considered as unusable EH. Several iterations were required, setting the initial storage level in the new iteration to the last value of the preceding iteration.

The cost correlations in Section 5.2.2 use the capacity of the equipment. Transmission pipelines, heat exchanger and heat pumps were dimensioned based on the maximum annual heat flows. The required TES size was found as the difference between the maximum storage level and the proceeding minimum.

Indicators

To compare the different industrial sectors according to their spatial, temporal, economic and thermodynamic suitability of delivering EH to DH areas, several indicators were introduced. The indicator in Eq. 5.7 compares the maximum deliverable EH to DH after demand limitations in the DH areas are accounted for with the theoretical maximum EH potential.

$$S_{\text{demand}} = \frac{\text{EH to DH with demand constraints}}{\text{Theoretical maximum EH to DH}} 100\% \tag{5.7}$$

The second indicator in Eq. 5.8 describes the ratio DH delivered through a thermal storage with the total DH delivered from EH source. This indicator thus describes the temporal mismatch between heat sink and source.

$$S_{\text{storage}} = \frac{\text{EH to DH delivered through TES}}{\text{Total EH to DH}} 100\% \tag{5.8}$$

The third indicator (Eq. 5.9) describes analogue to second one, the share of DH delivered through a heat pump with the total DH delivered. As the amount of EH requiring a heat pump, depends on the relation between DH and EH temperature, this indicator compares the efficiency at which the EH can source can be utilised.

$$S_{\text{HP}} = \frac{\text{EH to DH delivered through HP}}{\text{Total EH to DH}} 100\% \tag{5.9}$$

In Eq. 5.10 the COP of the heat delivered in each sector is shown.

$$\text{COP}_{\text{HP}} = \frac{\text{EH to DH delivered through HP}}{\text{Electricity needed for HP}} \tag{5.10}$$

In addition to these indicators, the weighted average mean specific heating cost, $\overline{c}_{\text{H}}$, was found for each industry category. Also the share of investment costs required for transmission pipelines, heat pump, heat exchanger and thermal storages will be analysed.

5.3 Results

5.3.1 Spatial and thermodynamic analysis of excess heat

First, the results of the geographical mapping of excess heat sources are shown, followed by the potential of using these sources for district heating.

Industrial Excess Heat

The mapping of the industrial excess heat is shown on the national level in Figure 5.8. The distribution of EH from thermal processes is spatially referenced to the 5 km by 5 km Danish square grid. It can be seen that the amount of excess heat varies considerably. The industrial regions around Aalborg, Fredericia, Kalundborg and Frederiksværk have the highest EH amounts. In these areas many companies from the heavy industry are found, such as cement manufacturing, steel processing and oil refineries. Around the Capital Region of Denmark a high density in the amount of industrial production sites are found. These industries however, emit only comparably small amounts of excess heat. The map in Figure 5.8 further magnifies an exemplary area, where the DH area and location of EH sources are shown.

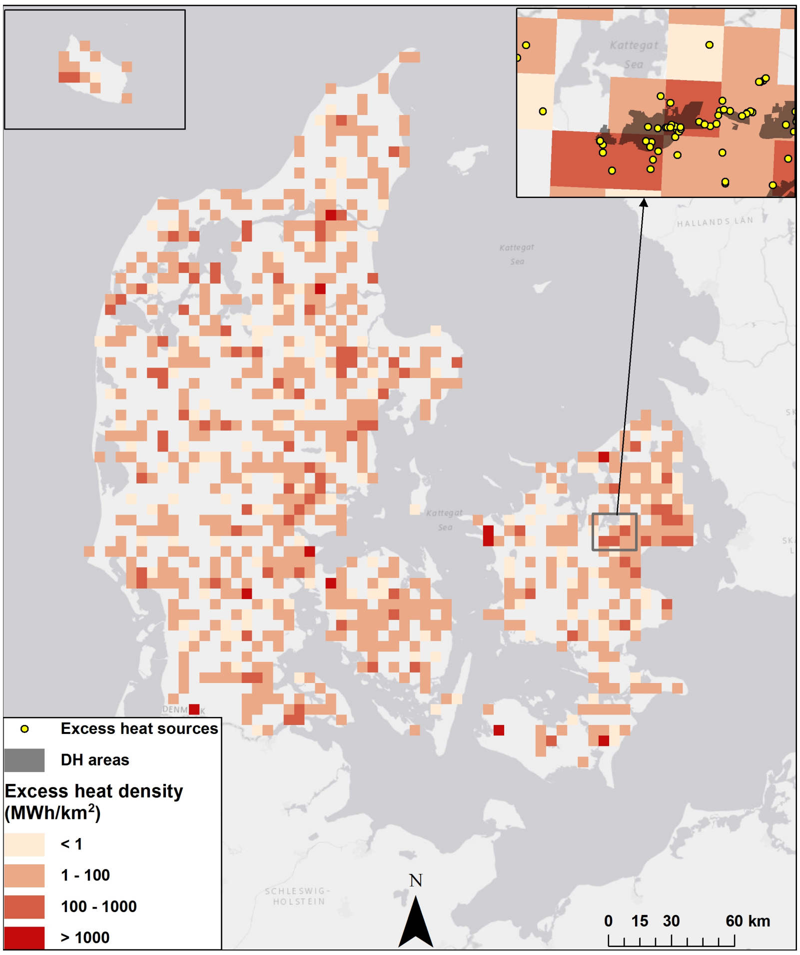


Figure 5.8: Excess heat from industrial thermal processes within 5 km by 5 km Danish Square Grid and example of data in the Roskilde area.

Industrial excess heat for district heating

The potentials for using EH for DH are presented in Figure 5.9. From the theoretical maximum excess heat potential of 3.43 TWh per year, 1.36 TWh of district heat can be supplied to the consumers. The theoretical excess heat potential is reduced by more than 1 TWh per year (from 3.4 TWh per year to 2.4 TWh per year), when the potential is corrected for inaccessible excess heat and unusable low temperature heat. This correction is mainly based on EH from flue gases which cannot be recovered and the limit of 40 °C for cooling down gases.

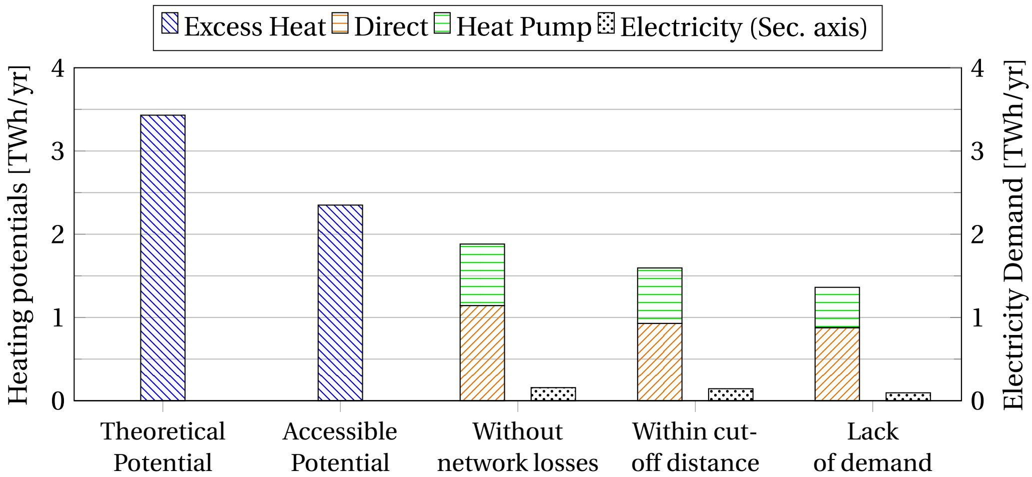


Figure 5.9: Potentials for supplying district heating demand from industrial excess heat sources.

However, not all excess heat is available for use in the DH networks. The recovery of the accessible excess heat is further reduced by considering network losses and eliminating excess heat sources which are outside of the cut-off distance. As shown in Figure 5.9, after the losses in district heating networks are taken into account, the heat which can be delivered is estimated to 1.88 TWh per year. The share of heat which cannot be economically transmitted to DH networks, due to large distances reduces the annual potential to 1.59 TWh (third bar in Figure 5.9). To obtain the real potential, the excess heat which cannot be used due to a lack of demand is taken out (0.23 TWh/year). In certain cases, there is not enough DH demand even though large excess heat sources are available. This limits district heating demand that can be covered from excess heat sources to 1.36 TWh per year or around 5.1 % of the existing DH demand (the most right bar in Figure 5.9). The remaining 0.23 TWh per year can be used for connecting the remaining consumers within DH areas to DH. The final annual potential of district heating supplied to the consumers is divided into 0.88 TWh originating from direct recovery and 0.49 TWh from heat recovery using a heat pump. The heat pumps would require 0.1 TWh per year of electricity, thus operating at an average COP of 5 when assuming a Carnot efficiency of 55 %. The distribution of the obtainable COPs for the connection of heat sources to the district heating networks is shown in Figure 5.10. With the majority of the matches, COPs of between 4 and 6 could be obtained. Almost as many matches are found in the range

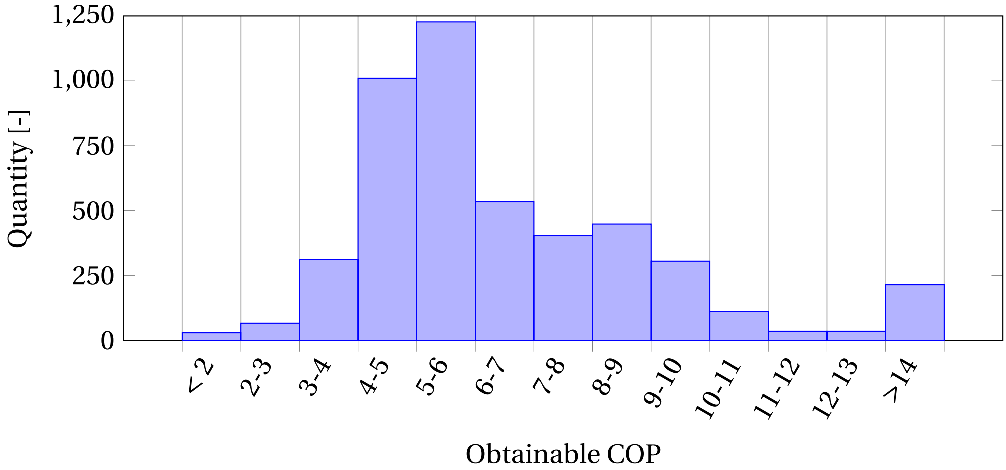


Figure 5.10: Distribution of the obtainable COP values for matches between excess heat and district heating networks.

of COPs from 6 to 10. The obtainable COP can give an indication of the required relation between electricity and heating prices, for a profitable operation of the system. In Table 5.5 the DH demand and substitution potential with EH is allocated to East Denmark (DKE) and West Denmark (DKW). A subdivision in central and decentral areas is further made. It can be observed that the distances between excess heat sources and district heating demand are especially important in decentral areas. Namely, 25 % and 50 % of available excess heat in East and West Denmark cannot be utilised because it is too far from the demand to be economically feasible.

The maximum coverage (EH/DH) from excess heat sources is 9 % and can be achieved in central district heating areas in DKW. After all constraints are taken into account, it is found that 5.1 % of district heating demand can be supplied from industrial excess heat.

The share of DH demand which can be replaced by industrial excess heat from thermal processes is shown on the map in Figure 5.11. Several large district heating networks, such as

Table 5.5: District heating demand and demand covered by excess heat directly or with a heat pump inside and outside the cut-off distance.

		EH within cut-off			EH outside cut-off		
Region	DH Demand [TWh/yr]	Direct [TWh/yr]	HP [TWh/yr]	EH/DH [%]	Direct [TWh/yr]	HP [TWh/yr]	EH/DH [%]
Central DKE	7.73	0.072	0.123	2.5	0.008	0.003	0.1
Decentral DKE	2.68	0.102	0.027	4.8	0.028	0.014	1.6
Central DKW	9.18	0.511	0.312	9.0	0.014	0.007	0.2
Decentral DKW	7.07	0.192	0.023	3.0	0.157	0.037	2.7
Total	**26.66**	**0.877**	**0.485**	**5.1**	**0.207**	**0.061**	**1.0**

the networks in Aalborg, Kalundborg and the South of Copenhagen, could have a high share (over 80 %) of their DH demand covered by EH.

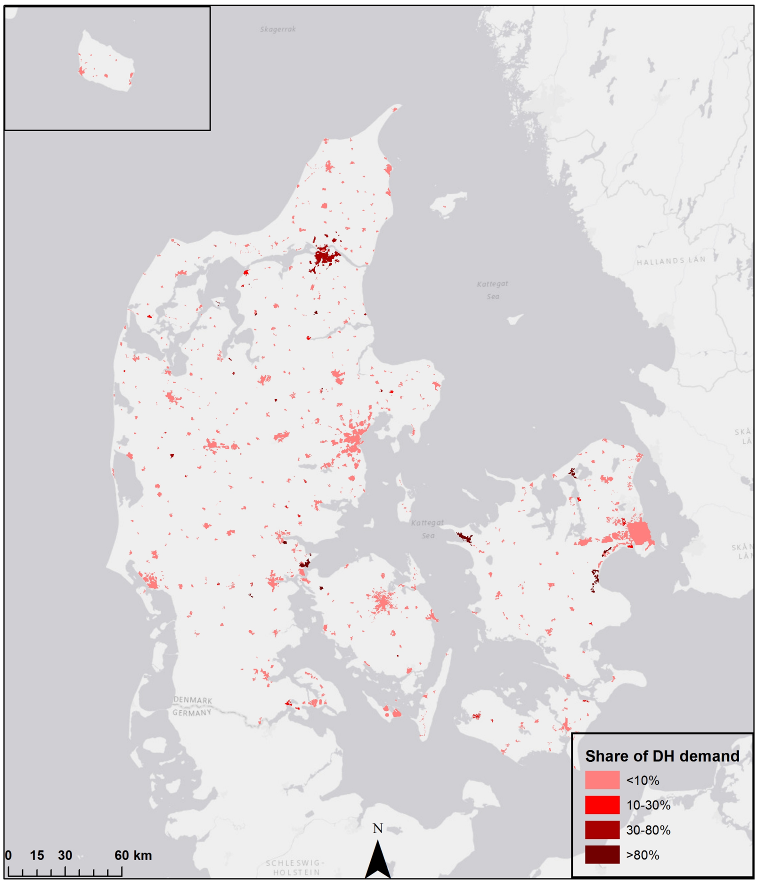


Figure 5.11: Danish district heating areas and the possible share of DH demand supplied by excess heat.

5.3.2 Temporal and economic analysis of excess heat

In the following the results including the temporal constraints and economic analysis will be presented in three steps: firstly, an exemplary case, secondly, the aggregated results, indicators and economic assessment, and thirdly, the sensitivity analysis.

Example case

To demonstrate the basis for the aggregated results, the evaluation of one industrial site is shown. This case study is a large meat processing plant located 3.2 km from the nearest DH area in Jutland, which has a supply and return temperature of 73 °C and 40 °C, respectively. In total 3300 MWh of EH are available each year of which 58 % are usable directly and the rest through a HP. In most cases the EH cannot be used directly because of temperature mismatching (including the ΔT) is above the EH temperatures. The share of direct EH utilisation could be increased by combining direct heat transfer (e.g. preheating the DH water) and HP, however these configurations would require detail technical planning [39]. The HP would increase the EH temperatures of 50 °C with a COP of 5.8 and for EH at 60 °C with a COP of 6.3. This results in a total DH utilisation of 3500 MWh of which 2700 MWh are supplied to consumers after accounting for transmission and distribution losses. Around 14 % of the heat supplied to the DH users originates from the TES and 40 % from the HPs. An example of a daily heat balance for the case is shown in Fig. 5.13. During the presented hours, there is more EH than HD, which leads to EH being stored. When the EH amount reduces after 5 pm, some heat from the storage is used. It can be further seen that the HD is first covered by direct heat transfer, followed by DH through the HPs. The economic evaluation shows that a specific heating cost of 55 € per MWh would be achieved with investment costs of around 1.65 M€. The majority of the investment costs (49 %) are required for transmission pipes to the nearest DH area, followed by 41 % for the HPs, 7 % for heat exchangers and 3 % for the TES. The majority of the operation costs are for the HPs, which require more than 200 MWh of electricity per year. The heating price could be reduced to less than 31 € per MWh if the investment only included EH sources which could be utilised without a heat pump.

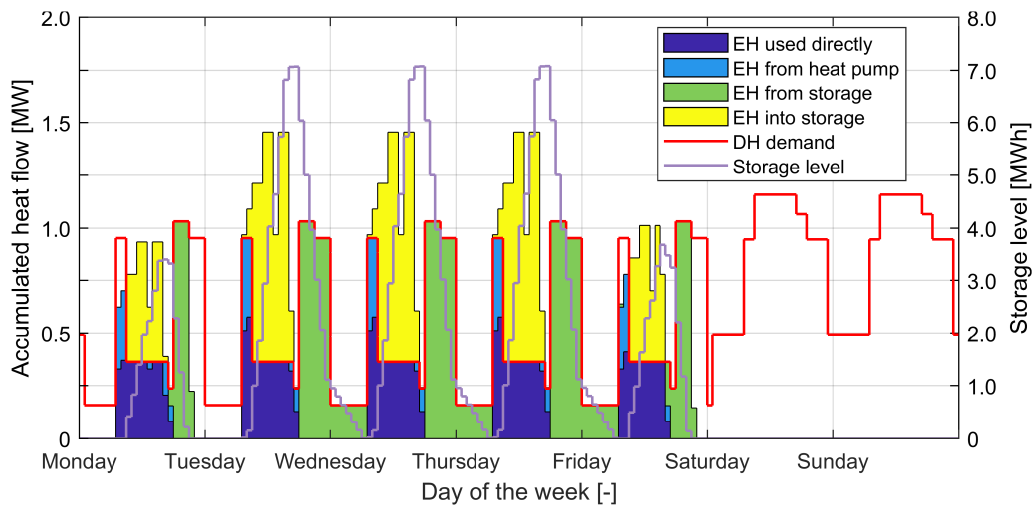


Figure 5.12: Example of the heat flows and energy balances during one week of the meat processing plant during summer.

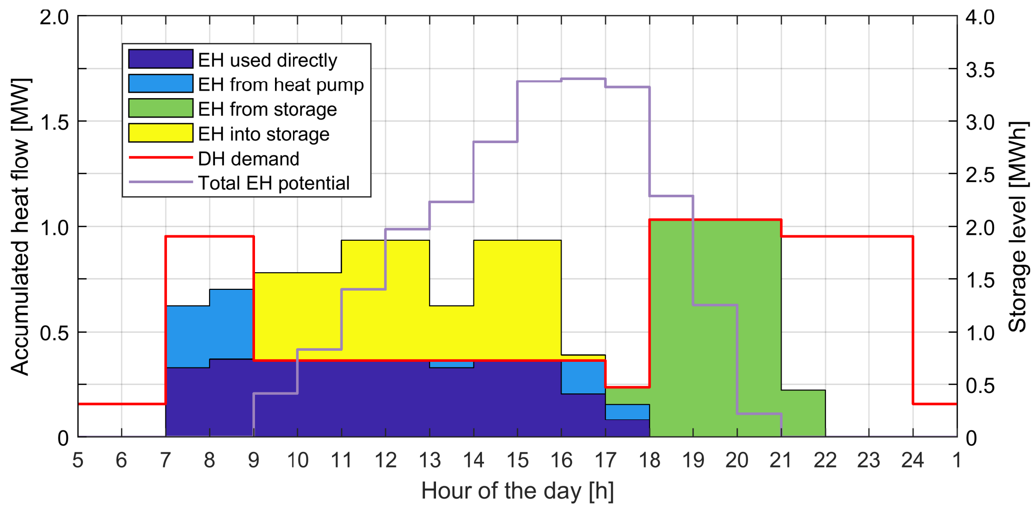


Figure 5.13: Example of the heat flows and energy balances during the first work day of summer in the meat processing plant.

Overall results

The results of the present study confirm findings of the first analysis (Section 5.3.1) that a maximum of 1.88 TWh of DH (5.1 % of the DH demand in Denmark) could be supplied from EH without any demand or distance constraints. This total potential is reduced by 27 % (to 1.37 TWh) when the temporal mismatch between demand and supply is considered. However, if thermal storages with unlimited capacities are considered, the potential is only reduced by 10 % because of a lack of demand, i.e. due to instances in which there is more EH than there is a demand for DH.

Spatio-temporal analysis

In Table 5.6 the indicators defined in Section 5.2.2 are shown for all industry categories. Based on the value for S_{demand} it can be seen that the EH from the food and building material industries is subject to minor limitations concerning the temporal patterns of EH and DH. This is in general due to constant production patterns of these industrial categories and the vicinity of DH areas with a high demand. The potential from oil refineries and metal production is, however, greatly reduced by the introduction of demand and temporal limitations. District heat supplied from EH from oil refineries and the cement production requires large thermal storages, as more than 20 % of the DH is delivered indirectly. This is due to pronounced seasonality of these industries, as described in Table 5.3. The food, chemical and non-metal minerals supply between 5 % and 10 % from thermal storages. The share of heat supplied by a heat pump varies greatly, as presented in Figure 5.14. More than 50 % of DH in oil refineries and non-metal minerals is supplied by HPs. This share is below 10 % for wood, paper and metal production, which makes them especially suitable for exploitation of EH for DH since

Table 5.6: Comparison of the utilisation potential of EH for DH by industry category based on the indicators defined in Section 5.2.2.

	S_{Demand} [%]	S_{Storage} [%]	S_{HP} [%]	COP_{HP} [-]
Gravel & Stone	93.4	12.9	60.2	4.8
Oil Refineries	75.4	19.3	82.3	5.6
Food	99.9	6.3	28.1	4.8
Sugar	100.0	0.9	29.9	2.6
Wood, Pulp & Paper	100.0	8.6	0.3	4.2
Chemical & Pharma	92.5	9.6	30.0	3.9
Cement, Bricks & Rockwool	94.8	31.1	13.3	4.3
Concrete products	100.0	1.6	18.5	6.3
Asphalt	100.0	7.2	33.9	7.5
Metal	75.0	6.4	6.4	4.6
Metal products	99.9	0.4	8.5	4.3

they do not require investments in heat pumps. The total COP for each category also shows that generally COPs above 4 can be expected, except for the chemical, pharma and sugar industry, where a larger share of low temperature EH is available.

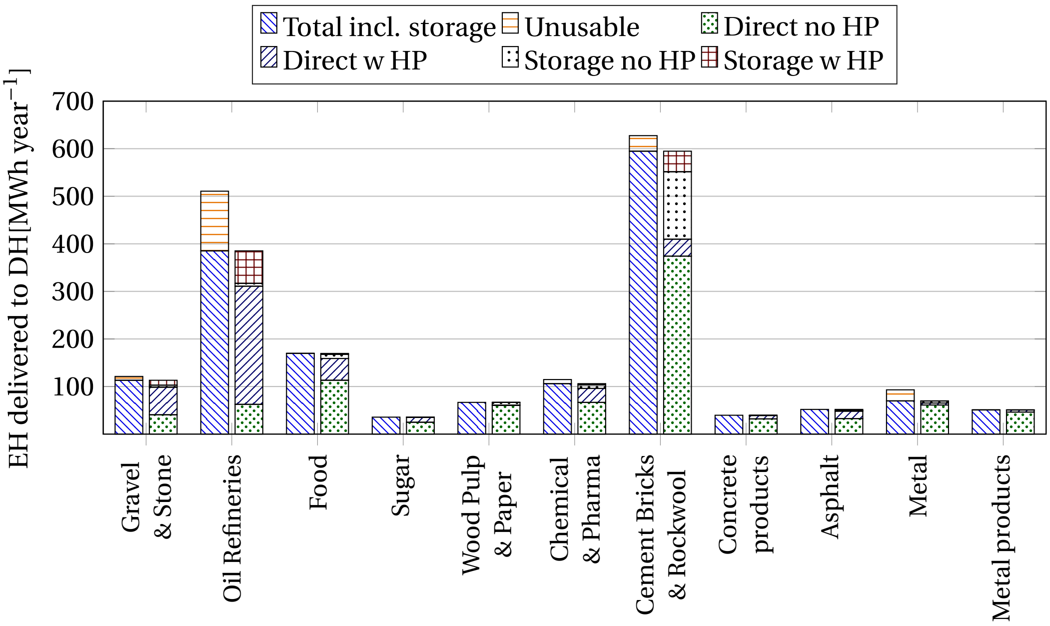


Figure 5.14: Industrial load profiles for thermal processes based on the number of shifts at the industrial site.

Economic analysis

The heating costs were found for each match between EH source and nearest DH network according to the cost estimation in Section 5.2.2. Figure 5.15 shows the resulting cost curve for the heating prices below 150 € per MWh. For the values greater than 150 € per MWh the curve becomes nearly vertical. Figure 5.15a shows that approximately 1000 EH sources can deliver DH at a price below 53 € per MWh, which was the average DH price in Denmark in 2016 [207]. Figure 5.15b shows the heating prices for the cumulative DH generation from EH. Almost 1.5 TWh can be provided annually at a heating price below 53 € per MWh. This indicates that the exploitation of larger EH sources is more profitable than of smaller ones, at DH prices lower than the 2016 average. In Figure 5.15b three flat parts of the curve can be identified, together representing around 0.75 TWh. These lines represent the three largest EH sources, namely cement production and oil refineries. All three sources can supply heat at comparably low heating prices. The weighted mean DH cost for all EH sources was found to be 35 € per MWh when including the cheapest 99 % of matches, which is cheaper than the average DH price in Denmark. The DH costs aggregated according to the industrial category can be found in Table 5.7. The development of the Danish energy system towards renewable

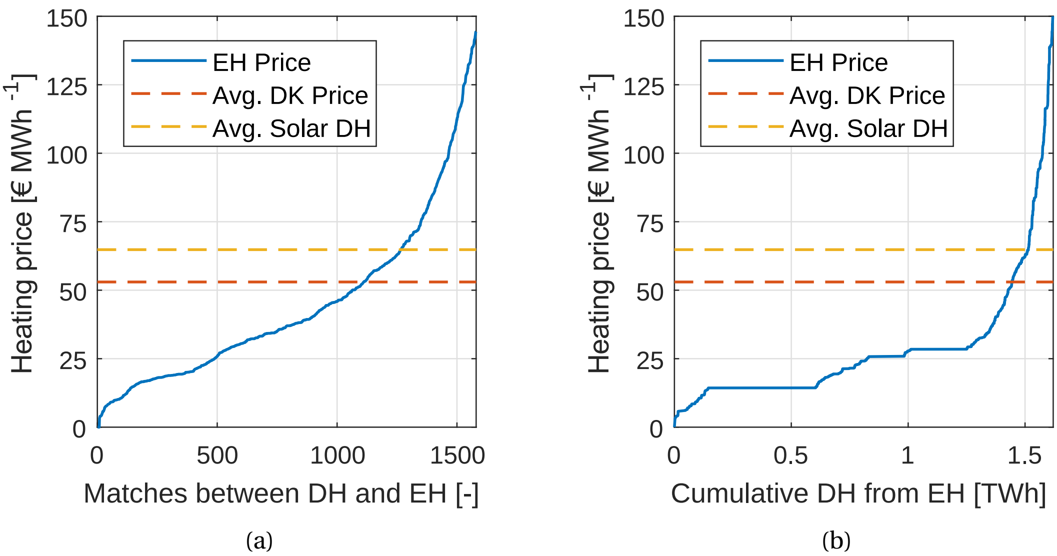


Figure 5.15: Cost curve of the heating prices below 150 € per MWh.

energy will lead to the change of DH prices. According to Ea Energianalyse [208] the future DH prices will be between 27.7 and 38.4 € per MWh in 2020 and will increase to between 32.6 and 45.7 € per MWh in 2035. It can be observed from Figure 5.15b, that these prices would result in a cost-effective potential of EH for DH between 1 and 1.5 TWh. Denmark experienced a strong growth of solar district heating installations in the last decade, increasing production by 16 times during the period [8]. The share of solar heating in district heating reached 2 % in 2017.

With 1.3 million m^2 of solar heating installations and a population of 5.5 million, Denmark has the highest area of solar heating collectors per capita. The favourable tax regime is one of the main reasons for its success. Therefore, the price of DH from EH is compared to the price of solar DH. The cost for solar district heat, when considering a thermal storage covering 100 % of the demand, is 64.8 € per MWh only including the costs for the solar system and storage [188]. This leads to the assessment that the utilisation of industrial EH can probably be in several cases more favourable from a socio-economic perspective to the one of solar DH. The distribution of the investment costs among the main system elements is shown in Table 5.7 and varies considerably among industry categories. Industries located far away from DH areas have a high share of investment costs in DH piping and tend to have a high cost for DH. The costs for thermal storages are only dominant for oil refineries and building materials, where large individual sources can be found and exceed the demand during summer. The production of metal products requires a large share of investment costs for piping. This is due to the relatively small size of thermal process related EH sources.

Table 5.7: Summary of the weighted average heating price and the total share of components of the investment costs for each industry category.

	$\overline{c}_H$ [€ MWh^{-1}]	$\mathrm{S}^I_{\mathrm{Pipe}}$ [%]	$\mathrm{S}^I_{\mathrm{HP}}$ [%]	$\mathrm{S}^I_{\mathrm{HEX}}$ [%]	$\mathrm{S}^I_{\mathrm{Storage}}$ [%]
Gravel & Stone	106	59.0	32.8	5.4	2.7
Oil Refineries	28	1.4	45.0	2.3	51.3
Food	81	80.1	10.6	6.2	3.0
Sugar	23	0.4	77.2	21.4	1.0
Wood, Pulp & Paper	134	92.6	0.1	3.7	3.7
Chemical & Pharma	118	84.9	9.4	4.3	1.3
Cement, Bricks & Rockwool	17	19.9	20.0	12.2	47.9
Concrete products	83	67.5	16.8	15.0	0.8
Asphalt	51	44.5	25.3	20.0	10.3
Metal	51	85.2	2.7	5.5	6.6
Metal products	348	96.2	1.0	2.8	0.1

5.3.3 Sensitivity analysis

Changes in future demand and supply

The share of district heating demand which can be supplied by industrial excess heat depends on several factors. First, the excess heat source can change as a result of efficiency improvements. Second, the transmission and distribution of EH through district heating network is also subject to change. Third, the district heating consumers can change as a result of heat saving measures. The most influential parameters for the utilisation of industrial excess heat for district heating are therefore varied to assess the sensitivity of:

- Share of district heating demand which can be supplied by industrial excess heat.
- Share of district heating demand which could be supplied from industrial excess heat but which is outside of the calculated cut-off distance.

The summary of the sensitivity analysis is presented in the following with detailed information being available in Appendix A.6. The sensitivity analysis included buildings which are located within existing district heating areas but are not supplied by DH as a potential heating demand. Furthermore a reduction of district heating demand by 30 % and 50 %, as a result of heat saving measures, demolition of existing and construction of new energy-efficient buildings was considered. The maximum heating demand which can be supplied by excess heat is 9.1 % of the district heating demand, when the heating demand in buildings is reduced by 50 % and all buildings within DH areas are connected to the DH grid. The heating demand supplied by excess heat did not double, as some DH networks have their demand fully covered by EH and can thus not increase the share.

Efficiency improvements and internal reuse of heat in industries, as described in Section 5.2.1, would be first implemented before district heating is generated. This would reduce the available excess heat. The energy efficiency improvements in industries were found to reduce the EH available for DH. However, the effect on the amount of EH which can be supplied to consumers is not major.

An increase of the "delivered-energy" weighted efficiency of DH networks in Denmark from 80.6 % to 85.6 % was further analysed [162]. This would increase the DH supplied by EH between 4.4 % and 5.0 %. This is expected and not a linear increase due to DH grids in which the EH is larger than the DH demand.

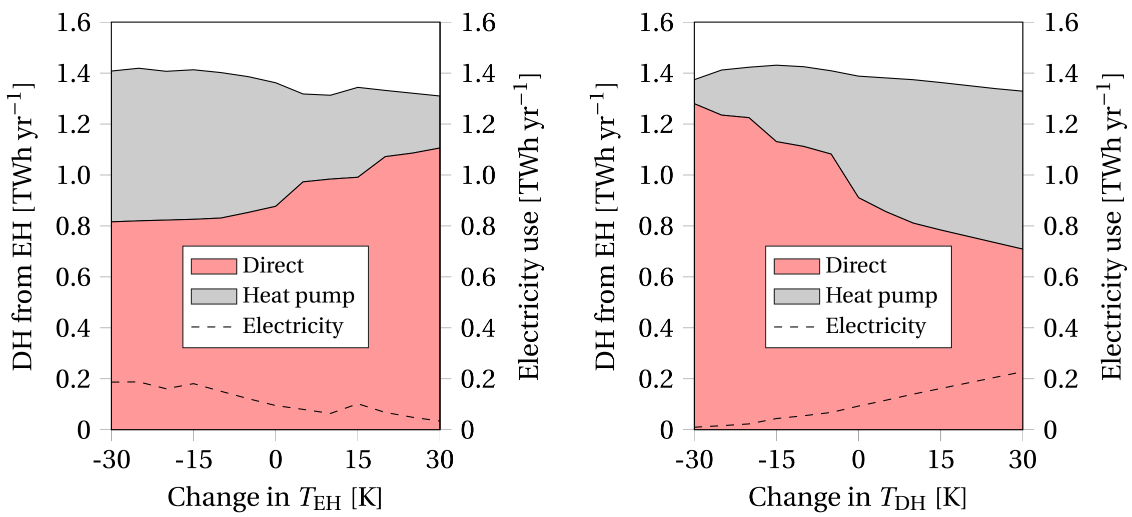
The combined increase in energy efficiency improvements in industries and DH grids are cancelling each other out, when considering the share of DH supplied by EH. A 50 % increase in heating demand and both energy efficiency improvements, increases the EH for DH potential to 8.38 % compared to 8.47 % without energy efficiency.

Sensitivity on district heat potential

The initial mapping of EH and its distribution amongst productions units is connected with a degree of uncertainty, in particular the amount and temperature of excess heat at each location. The assumption of a minimum temperature difference for the heat transfer was further based on generalisations. Despite the DH temperature being known with a high certainty, it might be necessary to add DH from the EH source at a higher or lower temperature. These factors were included in the following sensitivity analysis. For the DH temperature, the supply temperature was reduced, while keeping its absolute difference to the return temperature constant.

Figure 5.16 shows the impact of the temperatures on the DH supplied from EH by heat pump and direct heat transfer. A decrease in EH temperature reduces the DH supplied by heat pumps and decreases only marginally the total DH amount. In contrary an increase in the DH supply temperature increases the amount of DH from the HP. In Figure 5.16a, there is a sudden increase in EH from the HP at around 5 K increase in temperature. This is due to the low temperature EH from the cement factory, suddenly being above 60 °C, therefore having a $\Delta T_{\min}$ of 10 K instead of 5 K for its utilisation.

In Figure 5.17a it can be seen that an increase in the EH delivered from HPs is flattening from a 5 % increase in EH on. This is due to the EH amount of the refinery in Fredericia exceeding the local DH demand. As the majority of the EH from this refinery requires a HP, the flattening occurs primarily for DH delivered from the HP. Also the sudden drop in heat delivered by HP when modifying the minimum temperature difference, as shown in Figure 5.17b, is caused by this refinery. A large part of the EH is at 80 °C and the DH requires 70 °C. With a $\Delta T_{\min}$ of 10 K this heat require a heat pump. A small reduction in $\Delta T_{\min}$ allows the heat to be used directly.

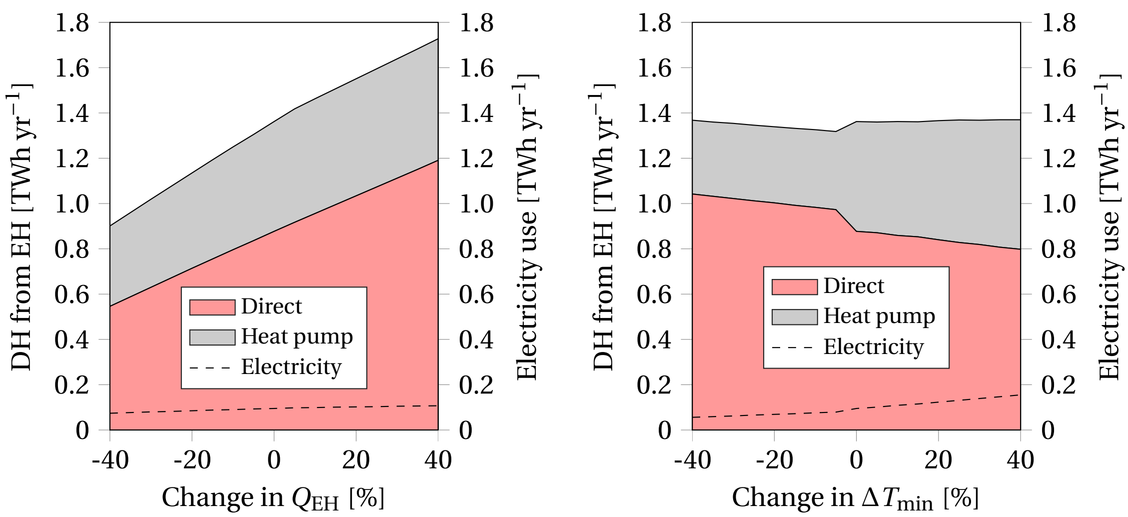


(a) Excess heat temperature

(b) District heat temperature

Figure 5.16: Sensitivity analysis of changes in the excess heat and district heat temperature (with constant temperature difference) on the district heat delivered from excess heat.

From this sensitivity analysis it can be seen that there are some large production units, which influence the overall potential of DH from EH. A relatively small change in the temperature for instance can have a disproportional impact. This is due to the size of the production unit but also due to the EH being initially grouped in temperature intervals. If there is a lot EH allocated to a temperature interval which is represented by a single temperature, a small change has a higher impact than if the EH was equally distributed across the interval.



(a) Excess heat temperature (b) District heat temperature

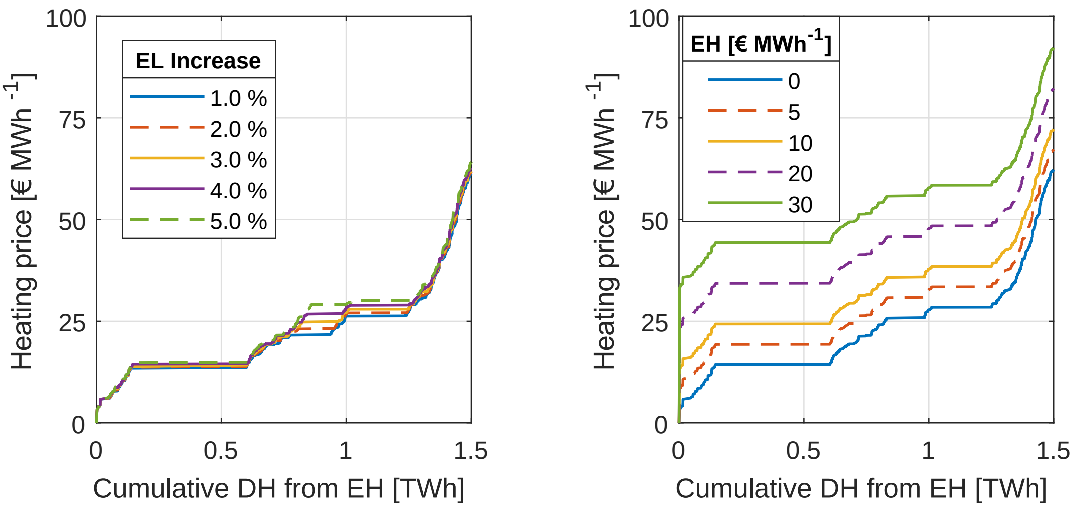
Figure 5.17: Sensitivity analysis of changes in the amount of excess heat and minimum temperature difference on the district heat delivered from excess heat.

Sensitivity on economic analysis

Also the performed economic analysis is subject to several degrees of uncertainty. Four major factors of uncertainty in the determination of the heating costs were investigated, namely the future development of electricity prices, the discount rate, the investment horizon and the assumption that the EH itself is available at no cost.

The future increase in electricity prices was estimated to 3.5 % per year until 2040 based on data from the Danish Energy Agency [204], which also recommends to perform a sensitivity analysis on this parameter as the development is very uncertain. The uncertainty in the future electricity price increase was included in the sensitivity analysis by varying it from 1 % to 5 % increase per year. As can be seen in Figure 5.18a, the future increase of electricity price has only a small impact on the EH potential for DH with heating costs below 50 € MWh^{-1}. Only for matches relying strongly on heat pumps (DH costs above 50 € MWh^{-1}), an impact can be observed, increasing the heating price by up to 5 € MWh^{-1}.

The assumption behind the results presented in Section 5.3 was that EH was available at no cost. This is not the case as it is for example for solar energy. The emitter of EH has (i) costs for the utilisation of EH even if, in theory, no investments would have to be performed. It will require internal process adjustments and working hours to initiate the project, to oversee the delivery of EH and general administration. There are also (ii) risks involved, (iii) lack of knowledge and business models, need for use of non-standard equipment, and (iv) ultimately the delivery of EH can decrease future options for fuel consumption reductions. This is in particular important as EH originates from e.g. the combustion of a fuel of which a part of the costs can be allocated to the EH. The industry has in theory thus a strong interest in reducing the EH amount or profit from its utilisation. It is however difficult to determine a global price of EH as it will depend on many local factors, of which many can be hardly quantified (e.g. risks and technology lock-in). Other works have estimated the price of EH at 15 € MWh^{-1} [209]. A sensitivity analysis was performed with 5, 10, 20 and 30 € MWh^{-1}, to see how such a cost would impact the potential. EH prices of up to 10 € MWh^{-1} would only marginally decrease the DH available at heating prices below 50 € MWh^{-1}. An EH price of 30 € MWh^{-1} reduces the potential by more than 50 %. However, a majority of the EH is still cheaper than solar district heating. In this work a uniform equipment and investment lifetime of 20 years was assumed.

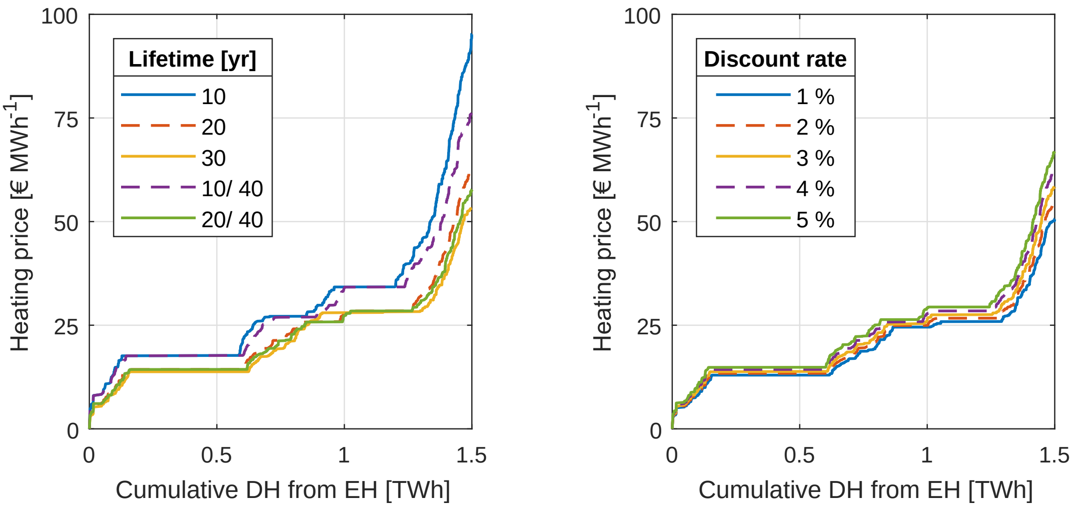


(a) Electricity price

(b) EH Price

Figure 5.18: Sensitivity analysis of changes in the future electricity price increase and cost of excess heat.

Some equipment, such as DH pipelines, will have a considerably longer lifetime [187, 202]. On the other hand, industries will probably use shorter depreciation periods for the investments into the heat recovery equipment. This will thus require the investments in the whole project to pay-off earlier. After the initial utilisation phase of EH for DH, of e.g. 20 years, it is not guaranteed that the EH delivery will continue. In addition, it is seen as very likely that during a 20 year period, the manufacturing processes will change significantly at a production site, changing the availability of EH. In the worst case, the DH pipelines will no longer be used, as they were built for a single purpose. In the sensitivity analysis the lifetime of the investment was varied between 10 and 30 years. Furthermore, the technical lifetime of DH pipelines of 40 years was coupled with the lifetimes of 10 years and 20 years for the remaining equipment as shown in Figure 5.19a. A decrease in lifetime of heat pumps and heat exchangers to 10 years would increase the costs only slightly and reduce the EH potential at a price below 50 € MWh^{-1}, by less than 250 GWh. On the other hand, expanding the lifetime to 30 years, has



(a) Lifetime

(b) Discount rate

Figure 5.19: Sensitivity analysis of changes in the discount rate and lifetime of the project. If two lifetimes are given, the second one refers to the DH pipelines.

only a notable impact for a few matches. By considering the technical lifetime of DH pipes, the potential can be slightly increased and unit costs for heat reduced. However, the lifetime of DH pipelines has generally a smaller impact on the cost-effective solutions, as they are characterised by low investment costs.

5.4 Discussion

This work found that 2.37 TWh of accessible industrial excess heat could supply 1.36 TWh of DH to consumers per year. If the temporal mismatch and demand limitations are included, together with seasonal thermal storages, the potential is reduced by 10 %. This is in line with 2.65 TWh per year used by Mathiesen et al. [169], 30 % smaller than 3.44 TWh per year used by Persson et al. [143] and Lund and Persson [178] and 80 % higher than 1.31 TWh used in the energy scenarios up to 2020, 2035 and 2050 published by the Danish Energy Agency [172]. However, 1.31 TWh per year used in Danish Energy Agency [172] is not directly comparable as it refers to the years 2035 and 2050. Contribution of industrial excess heat to supplying heating demand in the work of Möller and Lund [167] is between 83 GWh and 153 GWh per year, which is significantly smaller than 1.36 TWh per year estimated in the present study. Industrial excess heat is not included in the other studies [165, 166, 169], while the excess heat in Ref. Karlsson et al. [170] comes from biorefineries, which do not currently exist in Denmark and is therefore not comparable. The results are though not readily comparable to other works. For example, Mathiesen et al. [169] and Lund and Persson [178] do not elaborate on the potentials, while Persson et al. [143] does not consider temperature levels. However, the potentials calculated in the present chapter have the same order of magnitude as in Persson et al. [143], Mathiesen et al. [169], Lund and Persson [178].

The numbers used for EH as a resource in the different works are hardly comparable, as system boundaries are chosen differently and often the background of the numbers is not clearly stated. In this work a detailed mapping of excess heat and its temperatures has been performed, which only considers part of the industry but with a high level of detail.

Even though a detailed mapping of EH and linking of sources and demands has been performed, a couple of factors were not included. As only excess heat from thermal processes in 22 industrial sectors was taken into account, the total potential for district heat could be even higher. The total accessible excess heat potential from the manufacturing industry used in this study was 2.37 TWh per year, which is lower than the excess heat potential found for the whole industry. A previous comparable study [120], which also included EH from other processes and industries found an annual excess heat potential of 6.27 TWh. On the other hand, the actual potential for utilising excess heat can be smaller due to variations of excess heat sources and demand over shorter and longer time periods, taxes and polices, local and technical barriers.

The role of industrial excess heat in the future energy system, i.e. its effect on the investment and operation costs, fuel use, environmental emissions, etc. can be quantified by the use of energy system analysis tools. However, even if the energy systems analysis tools show that the utilisation of industrial excess heat is beneficial for the energy system as a whole, it needs to be ensured that these solutions also perform the best from a business-economic perspective. This can be done by introducing relevant supporting schemes, taxes and regulations. Not even well defined taxes and polices guarantee that the district heating companies will be willing to accept the industrial excess heat. The risk of industrial facilities changing production, closing or relocating, might not be accepted by district heating companies. Therefore, there is a need for the analysis of business models for utilisation of industrial excess heat.

Geographic distribution of excess heat

It is necessary to further evaluate the precision at which the distribution of the excess heat amongst single production units was conducted. A detailed analysis of the dairy sector was previously performed. For the majority of the dairy sites in Denmark, detailed information for total energy input, thermal and electric energy use for processes and facilities, raw material input and boiler and distribution losses were available. This information was gathered on a site-specific level.
Figure 5.20 shows a comparison of the applied method to allocate EH to each production site based on CO_2 emissions or number of employees. For each site, the EH was also distributed based on the real thermal process and total energy demand. In addition the thermal losses from boilers (excluding the production of electricity) and distribution losses in the factories steam network are shown.

It can be seen that for sites with a low energy use, where the number of employees was used,

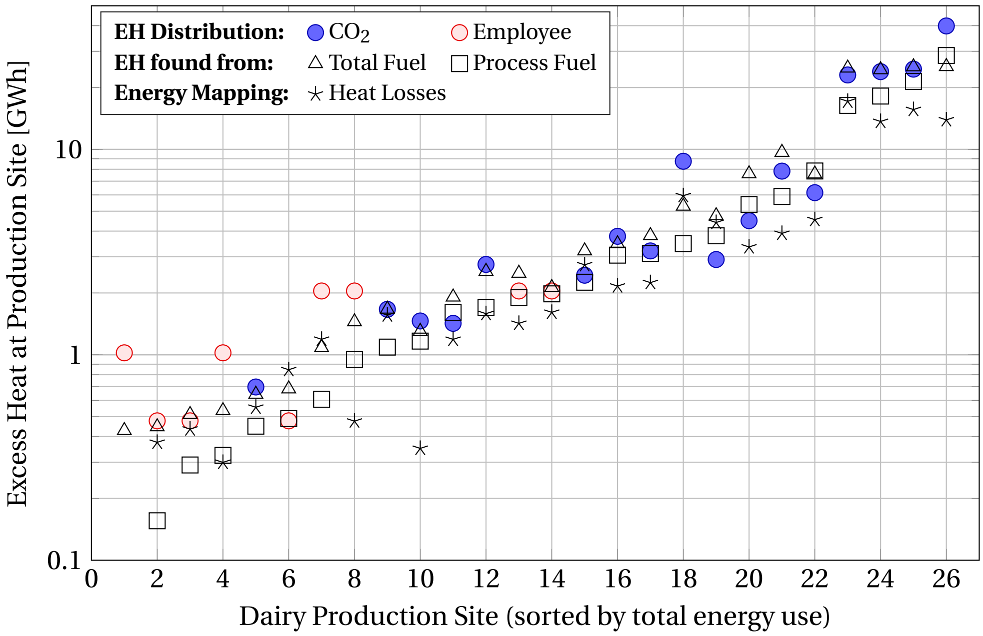


Figure 5.20: Comparison of allocated excess heat based on CO_2 emissions or number of employees to data obtained by energy mappings at the individual sites.

the EH tends to be slightly overestimated with the proposed method. For energy intense sites, the EH allocated with CO_2 emissions correlates closely, with a tendency of underestimation, to the distribution using the real process energy demands.

The boiler and distribution losses were at most sites lower than the total excess heat allocated. Other sources of EH exist at the site, especially for large units. For example, the production of milk powder results in considerable excess heat from drying and evaporation facilities.

For the production of asphalt, site-specific CO_2 emissions were not available. The distribution relied solely on the number of employees registered and is thus expected to be the most uncertain distribution. For two factories in Denmark, the actual excess heat of the direct fired rotary dryers were known based on a detailed analysis. The dryer is the primary source of excess heat in the production of asphalt [210]. For the first factory excess heat of 2.69 GWh per year and for the second one 0.89 GWh per year were found. The distribution of excess heat using the proposed method, allocated 3.83 GWh per year to each of the two factories. The difference between the estimated and actual EH amount, shows that the order of magnitude is comparable and a reliable indication can be given. For companies manufacturing the same product and employing a comparable number of people, the real EH amount may however be different. This is not represented when performing the EH allocation based on employees registered in the CVR.

Economic analysis

The economic analysis performed in this chapter aimed at determining the socio-economic heating cost for using EH for DH. Several assumptions and simplifications were made, however it was possible to use this approach for all 2584 EH sources mapped in Denmark. When considering a private-economic heating price, several other parameters will have an additional influence. There are currently subsidies available for systems comparable to the ones studied [211], however the delivered heat might also be subject to taxes [212]. In addition the chosen ownership model, a high perceived risk of the investment and the cost of financing such a project, might increase the overall heating price. On the other side, additional cost savings might be possible as in some application the heat pump might supply a cooling need and thus reduce energy used for current refrigeration systems. Also, no economic optimization was performed leaving the opportunity to reduce storage tank and equipment sizes, which were dimensioned after the peak heating load. Finally, new business models are required to split the benefits between industries and utility companies. Altogether, each case has to be evaluated individually if a robust result is required.

Future electricity prices can affect the cost-effectiveness of EH which requires HP to become useable. If the electricity prices go down, this EH would become cheaper. On the other hand, high electricity prices usually go hand in hand with high environmental targets. In the case of high renewable energy targets, EH becomes very important in the future energy system. It seems reasonable that EH should be used, from a socio-economic perspective, with both high and low electricity prices. However, this requires a full energy system analysis, which is part of future research using TIMES-DK [213, 214].

The refineries and building material industries were identified as the most profitable ones, due to the large size of the individual EH sources. On the other hand, they require large seasonal storages. The installation of these storages should be possible in most cases, as these industries are placed outside of densely built areas. The food, asphalt and basic metal industry can also have low heating prices and good thermodynamic properties. Even though piping accounts for a large share of the investment in these industries, a high share of direct heat transfer and high COPs can be obtained in combination with small storage sizes. Therefore, if a food, asphalt or basic metal industry would be located in a densely populated area, installation of a thermal storage should not represent a problem.

Applicability of the method

The results of this chapter can be partly used for first assessments of other countries. The following needs to be considered for the results. Besides the industry characteristics, the COP depends on the local DH network supply and return temperatures. These DH temperatures can be generally higher or lower in different countries, affecting the obtainable COP and the share of EH requiring a HP. This has a direct influence on the heating price in each industry category. Industry categories, dominated by a few production units, such as oil refineries and

cement production in Denmark make some results not directly applicable to other countries. If the EH originates with a majority from one source, its location will influence the whole category. This is in particular the case for the maximum deliverable EH to DH (S_{demand}), where the demand of a specific DH area can influence the overall results. In this study, specifically oil refineries and cement plants have a great influence on the outcome of their respective categories. Both are very energy intensive and only a few factories exist. This can also be seen in the horizontal parts of the heating prices plotted against the cumulative DH demand covered by EH in Figure 5.15b.
The method described in this work is applicable to other countries. It relies however on previous works, which use data specific to Denmark which might not be available for all countries. The required information on a national level for this analysis is the energy demand of industrial sectors and its distribution amongst thermal processes, as well as heating demands and temperature levels of the DH areas. This information can be used to create the spatial model and determine heating prices of all matches.

In this work a sensitivity analysis, varying one factor a time, was conducted for four assumptions which were expected to have an impact on the results. From these only the EH price and lifetime of the equipment were found to have a significant impact on the cost curves. There are several other parameters which have a high uncertainty, such as excess heat temperatures, minimum temperature differences, investment costs, operating costs and real connection distances. Also the amount of EH which is based on disaggregated national energy use data is connected with a high uncertainty. On a case study basis, [215] determined the uncertainty of heating prices and determined the important model parameters using advanced sensitivity analyses. It was shown that the EH temperature can contribute significantly to the uncertainty of the result. Especially in cases where the EH temperature is close to the DH temperature, a small change in the temperature can decide between the requirement of using or not using a heat pump. This has great impact on the investment but more importantly on the operating costs.

Future research should focus on extending the scope of the EH mapping, including other EH sources such as data centres, supermarkets and other industrial sectors. It is further necessary to determine the degree of possible internal heat recovery at the site, which would require the analysis of the heating demands and industry specific potentials for process integration. A tool for determining cases for EH recovery based on the spatial model was developed [215], where also uncertainties have been assessed. An assessment of uncertainties of the overall potential and the mean heating price, would add further important information. Also the development of the industry in the future (e.g. electrification of processes), the costs of electricity and developments in DH systems (e.g. low temperature and ultra low temperature) has to be assessed on how they impact the role of industrial EH as a source for DH. The DH profiles could be further refined, e.g. changing the length of the different heating seasons, to better reflect the real consumption. It is however expected that this will only affect the results marginally.

5.5 Conclusion

In this chapter excess heat sources from the industrial sector in Denmark and how they could be used for district heating were analysed. Both a method for the analysis and results of the case study have been presented. The developed method first quantified excess heat at single production units, together with industry specific temperature profiles and performed a spatial analysis to link excess sources with buildings. For each linkage a thermodynamic analysis was performed to quantify the amount of generated DH and determine the requirements for heat recovery. The amount of delivered DH was further refined and analysed from a socio-economic perspective. This was done by including the temporal patterns of DH demand from different user types and the temporal availability of EH described in relation to the industry type and size. For the economic analysis investment costs for heat pumps, heat exchangers, thermal storages and DH piping were included to find the simplified socio-economic costs of provided district heat.

The results for Denmark show that 5.1 % of the existing district heating demand could be theoretically supplied with industrial excess heat from thermal processes. This potential is not uniform, it is high in industrial regions around Aalborg, Fredericia and Kalundborg, while it is low in the Capital region. This means that industrial excess heat cannot be a dominant source of district heating on the national level, but can be very important in some local district heating systems. In total 1.36 TWh per year of district heat could be supplied from industrial excess heat. A heat pump was required for 36 % of this district heat, as the temperature of the excess heat source was too low. The required heat pumps would operate at an average COP of above 5, thus requiring 0.1 TWh per year of electric energy.

The spatial analysis enabled to investigate the maximum distances between excess heat sources and the demand. Also the situation when the excess heat is larger than the heating demand was analysed. Both proved significant as each of them reduces the available excess heat by approximately 15 %. When also the temporal mismatch of sinks and sources, as well as demand limitations, were considered the technical and spatial EH potential was reduced by 27 %. The use of TES reduced the temporal mismatch, leading to the decrease in potential by only 10 % compared to the values without temporal mismatches and demand limitations.

The weighted mean DH cost was found at 35.6 € MWh^{-1}, however the distribution has a long tail spreading the possible costs. Almost 1.5 TWh of EH can be utilised at heating prices below the 2016 Danish average price of 53 € MWh^{-1}. Industries which have in general larger production sites, have low sectoral DH costs. This is partly due to the ratio of piping costs to EH size. Particularly low heating prices were found for oil refineries, food industries and the building material as well as basic metal production.

The sensitivity analyses showed that the results are not very sensitive to the considered efficiency improvements in the industry, district heating grids and buildings. The simultaneous reduction of heating demand in buildings by 50 % and increasing the efficiency of district heating grids by 5 percent points has the highest impact. In this case, industrial excess heat can supply 8.9 % of district heating demand in buildings. The effect of efficiency improvements in the grids and in the industry are cancelling each other out. The costs for the delivered heat are most sensitive to the price of EH, if there is any, and the lifetime of the project.

6 Identification and evaluation of cases for the utilisation of excess heat

This chapter presents a detailed analysis of cases for the utilisation of excess heat. A systematic approach for identifying these cases is proposed, considering production of district heat and process heat, as well as power generation. The technical and economic feasibility of six cases was evaluated for six cases, accounting for uncertainties of the results and identifying the most important model parameters.

6.1 Introduction

As shown in Chapter 5 a potential for the utilisation of industrial excess heat was identified. This potential was shown to be in many cases cost-effective exploitable from a socio-economic perspective. There are several barriers to energy efficiency and excess heat utilisation which impede the implementation of such projects. These barriers are discussed in Chapter 9. With respect to excess heat utilisation, several studies [138, 179, 180] agreed that a lack of available information and knowledge about excess heat sources and possible excess heat users are a major barrier for the utilisation of excess heat. Structural barriers, such as the lack of infrastructure for heat transmission, and a limited technical recovery potential were identified as additional barriers. Economic barriers also play an important role, such as the initial costs of obtaining information and missing governmental frameworks.

Brückner et al. [216] investigated the utilisation of waste heat for residential heating in an urban neighbourhood in Germany and performed an economic analysis of heat transformation technologies for industrial waste heat [173]. For Sweden, Broberg et al. [135] estimated the potential of industrial excess heat for Swedish district heating networks and showed, based on cost calculations, how excess heat investments become profitable. Viklund and Johansson [136] further reviewed the technologies for the utilization of excess heat and estimated their potential for a region in Sweden. Eriksson et al. [217] analysed the economic performance of exporting industrial excess heat from a chemical complex site in Sweden. A heat sale price of 200 SEK per MWh was found most probable. The uncertainties and complexity of the local heat market made an investment focused in delivering district heat the more risky option compared to recovering heat on site. Karner et al. [177] modelled synergies of industrial sites with urban areas, considering the use of industrial heat for urban heating. The results showed that for heat related investments, the profitability was given even without investment funding and that there was a high difference between heat pump and direct utilisation cases. Li et al. [218] analysed and optimised different configurations for a district heating network based on a distant low-temperature industrial excess heat source. For the case of Northern China the authors found that even if the heat source was distant, the economic and environmental advantages justified the excess heat utilisation.

The work presented in this chapter took origin in the applied methods and case studies of Chapter 5 and is based on [P6] and [C9]. This chapter provides a method to overcome some of the barriers to excess heat utilisation. The presented work is a fast and comprehensive method for identifying utilisation potentials of excess heat, and evaluating their technical and economic feasibility is required. The tool allows energy planners, district heating operators and industrial plant managers to find synergies between emitters of excess heat and heat demands on a local level and quickly assess specific cases, before performing detailed analyses. It extends the current state of research by spatial and economic analyses of excess heat sources and possible users, including uncertainty and sensitivity analyses. This method builds on the application of Geographical Information System (GIS) based data on excess heat and heating demand to identify and evaluate the feasibility of relevant cases for the utilisation of excess heat. The evaluation of the feasibility was based on technical practicability as well as economic indicators for each case. By using uncertainty and sensitivity analyses, the validity and confidence intervals of the method were analysed.

The approach and method for identifying potential synergy cases and the background of the data is first described in detail. Based on exemplary identified excess heat cases with GIS, six were selected and further analysed. This analysis included (i) technical considerations, such as the annual time profiles of heat sources and sinks, the available and required temperature levels, (ii) economic considerations for the investment in new equipment and its operation, (iii) governmental frameworks (e.g. taxes, subsidies) and (iv) environmental considerations, such as the type of replaced heating fuel and saved GHG emissions. Eventually an uncertainty analysis of the models was conducted to determine the confidence of the result and a sensitivity analysis was performed to determine the most important input parameters to allow an optimised application of the model.

6.2 Methods

In the following, the method for evaluating the feasibility of excess heat (EH) utilisation for the supply of different energy demands is shown. The overall method and set-up of the tool is shown in Figure 6.1. Based on data for the excess heat and heat demand, a GIS mapping was performed which was used to identify opportunities to recover EH. Based on the identified case, first a thermodynamic evaluation followed by an economic one was performed. For the model outcomes of these two evaluations, an uncertainty and sensitivity analysis was conducted. This allowed a targeted refinement of the key parameters, to increase the confidence in the model output. At the end, the results of the economic evaluation, including the uncertainties, together with an environmental assessment were used to evaluate the overall feasibility of the cases and take the investment decision. These results can then be used to take a decision, if further investigations by e.g. consultants should be made.

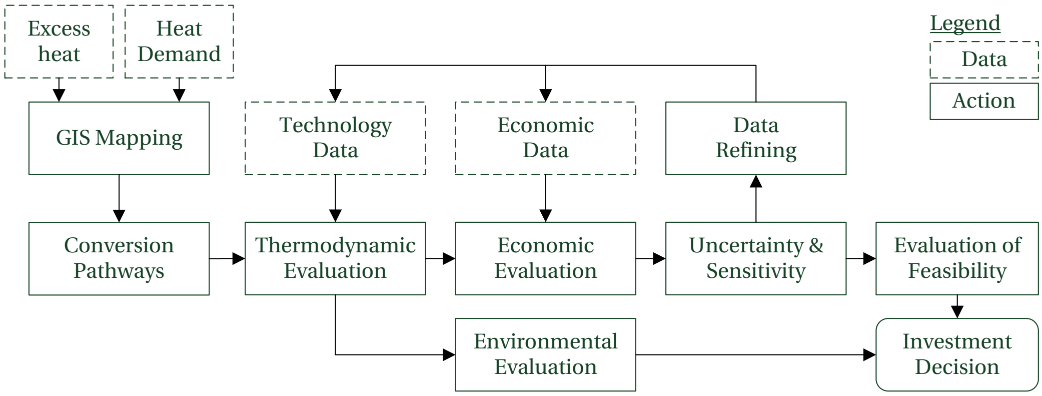


Figure 6.1: Overview of the method for evaluating the feasibility of different cases for the EH utilisation potentials.

6.2.1 Geographical mapping and identification of synergies

The work in this section originates from earlier studies where industrial excess heat from thermal processes and its temperature levels were determined for production sites in Denmark [91, 181, 182] and the method for case identifications was presented [215]. The work showed the potential of using industrial excess heat for district heating in Denmark. In the current analysis an identical distribution key was used to include other industrial excess heat sources, as they were found in [219]. Excess heat from the utility sector (power and heating plants) and waste water treatment (WWT) plants was further included. The aggregated EH data was distributed to specific locations using the individuals plants thermal or electric capacity [171] and the amount of treated waste water [220]. District heating areas [221] and their respective heating demands, fuel use and heating costs [185] were further integrated in the GIS model. All the above data was integrated and analysed using QGIS [222], an open source GIS software, with map material from OpenStreetMap (OSM) [223].

In this analysis, the utilisation of excess heat for heating of buildings or industrial processes, as well as the generation of electricity, was considered. To identify specific cases where the use of excess heat could be feasible, the detailed evaluation of the technical and economic feasibility of these cases was performed as follows:

1. Evaluation of the maximum amount of industrial EH which can be converted to district heat substitution, as performed in [181].
2. Identification of district heating areas with high substitution potential. Analysis of the excess heat sources responsible for the high potential in GIS.
3. Assessment of the EH sources: Sector of the match and company, typical excess heat amount and temperatures for processes of the sector and determination of the distance to the nearest heating area. For each heat sink, the most suited heat source were considered.
4. Economic and technical evaluation of the case: This requires the estimation of typical operating hours and profiles, as well as determination of current heating prices, investment and operating costs.

In case of synergy between two industrial complexes, the replacement of process heat with excess heat was considered in a similar manner. Instead of step 2, clusters of excess heat were identified. Such clusters indicate the presence of several companies within the industry and utility sector. From the excess heat and process temperatures of individual sites, matches could be found.

The evaluation of cases for electricity production were found by identifying industrial sites which either have (i) high-temperature excess heat (> 150 °C) from other sources than off-gases from boilers or (ii) are in isolated locations.

The technical and economic evaluations of the matches were performed as described in Section 6.2.2 and 6.2.4, with the aim of obtaining an indication of the feasibility which justifies further analyses. To perform the feasibility evaluation, the following characteristics were required: the temperature and the amount of EH, the classification of the industrial sector, as well as the temperatures, capacity and type of the heat sinks. This information was included in the GIS model for each site on a sectoral level, however further refining of the data was required for the individual process by using information from the literature.

6.2.2 Utilisation of excess heat

The utilisation pathways for the use of excess heat, considered in this work are shown in Figure 6.2. Three technologies were considered, namely direct heat transfer, heat pumping and Organic Rankine Cycles (ORC). The considered heat sinks were: industrial sites requiring process heat, heat demand of buildings and the electrical grid.

The direct utilisation of the excess heat was performed as described in the Section 2.4. The heat pump was modelled considering the Lorenz COP. A combination of direct heat transfer and heat pumps was not considered.

The third option was the use of an ORC to generate power from the excess heat in cases where no suitable heat sink was present or if the temperature of the excess heat was high and power

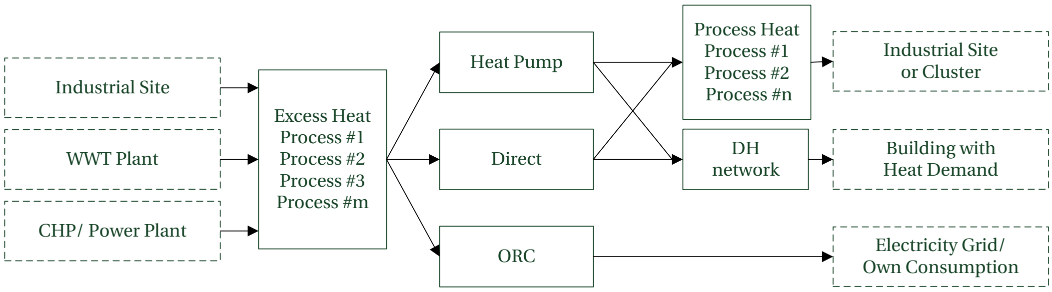


Figure 6.2: Utilisation pathways for excess heat from different sources.

generation was seen as the favourable option. In those cases, the electrical efficiency of the ORC mainly depended on the excess heat temperature. In this work, the efficiency of the ORC was found using Eq. 6.1. The theoretical efficiency of converting heat to power is described by the Carnot efficiency η_{Carnot}. To obtain a more realistic result, the Carnot efficiency is multiplied with an electrical efficiency, η_{el}, which is between 30 % and 50 % for EH sources in a temperature range of 100 °C to 350 °C. The choice of the electrical efficiency was based on literature correlations [92, 136, 224] and T_0 was set to the environmental state at 25 °C.

$$\eta_{\text{ORC}} = \eta_{\text{el}}\,\eta_{\text{Carnot}} = \eta_{\text{el}}\left(1 - \frac{T_0}{T_{\text{EH}}}\right) \tag{6.1}$$

The minimum temperature difference considered in this work was 5 K for streams below 60 °C, which were assumed to be liquid and originating from e.g. condensate or compressor cooling. For streams above 60 °C, a value of 10 K was used, accounting for the mainly high-temperature exhaust gas flows. It was further chosen to set a minimum outlet temperature for EH streams to 40 °C if they were above 60 °C and to 15 °C if they were below. Only for waste water, a constant temperature difference of $T_{\text{EH,in}}$ to $T_{\text{EH,out}}$ of 6 K was chosen [225]. If the DH return temperature was above the minimum outlet temperature, the return temperature was used.

To determine the investment costs, the heating capacity of the heat pump and the electric power for the ORC were used. In the case of a direct heat transfer, the area A_{HEX} of the heat exchanger was found using Eq.6.2, where LMTD is the logarithmic mean of the temperature difference in counter-current heat exchanger and k the fixed overall heat transfer coefficient.

$$\dot{Q}_{\text{H}} = k\,A_{\text{HEX}}\,\text{LMTD} \tag{6.2}$$

6.2.3 Excess heat and heating demand

The excess heat source, as well as the heating demand, are often not constant over time. It was thus necessary to account for their operating profile in relation to each other. In this work,

Table 6.1: Summary of the thermodynamic model parameters and their distribution in the input uncertainty space for the evaluation of the case studies. (Uniform U[lower;upper]).

Item	**Value**	**Unit**	**Uncertainty**	**Source**
HP efficiency ($\eta_{HP,lorenz}$)	0.55	[-]	U[0.45;0.65]	[92, 226, 227]
ORC efficiency ratio (η_{el})	0.35	[-]	U[0.3;0.4]	[92, 136, 224]
k (gas/liquid)	42.5	[W m^{-2} K^{-1}]	U[15;70]	[195]
ΔT_{min} for $T_{EH} > 60\,°C$	10	[K]	U[8;12]	
ΔT_{min} for $T_{EH} < 60\,°C$	5	[K]	U[3;7]	
T_{min} for $T_{EH} > 60\,°C$	40	[°C]	U[35;45]	
T_{min} for $T_{EH} < 60\,°C$	15	[°C]	U[10;20]	
ΔT_{WWT}	6	[K]	U[4;8]	[228]

seasonal profiles were used to correct the possible utilisation of excess heat towards different source and sink profiles. The profiles allocate the heat demand and supply over four quarters of the year (Q1 to Q4). Q1 represents the heat demand in the three first months of the year, Q2 the following three months and so forth. Two profiles were created for heat demands (DH1 and DH2) and four production profiles were considered for the industrial plants (PP1 to PP4). The industry profiles take into account that some industries have a constant production (e.g. chemical and food industry) and some have a higher production during warm periods or vice versa (e.g. building materials). The first heat demand profile, DH1, follows the annual residential heating demand. To account for situations where the summer heat demands in a DH area are covered by waste incineration plants or solar heating, and thus no additional heat is needed, the DH2 profile was created.

Table 6.2: Distribution profiles for the district heating (DH) demand and excess heat from processes (PP) over one year in percent.

Quarters	DH1 [%]	DH2 [%]	PP1 [%]	PP2 [%]	PP3 [%]	PP4 [%]
Q1	40	50	25	20	10	30
Q2	15	5	25	30	40	20
Q3	10	0	25	30	40	20
Q4	35	45	25	20	10	30
$\sum$Q	100	100	100	100	100	100

Another factor which was critical for the determination of the particular sizes of equipment as well as economic feasibility was the annual operating hours of a source or sink. If the excess heat is emitted in relatively small periods of time, the maximum power will be higher and require larger components. To account for variations of the operating hours, a selection was made based on the number of working shifts at the site. Typical operation profiles allow for three shifts, which was translated into 3200, 5000 or 8000 operating hours a year. There are also daily variations of the sink and source, however it was assumed that these variations can be neglected as storage tanks of reasonable sizes could be implemented and act as buffers between supply and demand.

6.2.4 Economic evaluation

The economic evaluation of each case study was performed by determining the economic feasibility, based on the Investment (I) and the Operation & Maintenance (O&M) costs. The framework for investment was accounted trough inflation, interest rates and future change in energy prices. Investment and operating costs are presented in Section 6.2.4. A separate focus of the economic analysis was the inclusion of taxes and subsidies in Denmark and how they influence the feasibility of the projects. An elaboration of this aspect is further presented in Section 6.2.4.

Investment and operating costs

The considered investment costs for utilising the excess heat in this work consisted of the piping between heat source and sink, heat exchangers and heat pumps, as well as investments in equipment for an ORC if electricity was to be produced. Investment and maintenance costs were found using the Danish Technology Catalogue [188] and for piping the summary by Nielsen and Müller [187]. The equipment lifetime of 20 years for the economic analysis was chosen to be equal in all cases and for all equipment. Some equipment, i.e. DH pipes, will have a longer investment horizon than others, e.g. heat pumps. The found investment costs were seen as direct costs (DC), to which indirect costs as a fraction of the DC were added [21]. The investment costs were then obtained by deducting investment subsidies and adding interest payments on loans.

District heating prices were found for each heating area in the price statistics of the Danish Energy Regulatory Authority [229] which were used to correct the overall substitution given in Table 6.3. Future increases in DH prices depend on the specific DH area, in particular if it is a central or de-central area[1] and the size. Different predictions were found, but a uniform prediction over all areas was chosen in this work [208]. It was further assumed that no costs were initially allocated to the excess heat and that the investment was performed by the owner of the excess heat source.

[1]The *Energy Producers Count* [171] groups district heating producers into central and decentral, which supply the respective areas. Central DH areas have higher heat demands, installed capacities and transmission efficiencies compared to decentral DH areas.

Table 6.3: Summary of the economic model parameters and their distribution in the input uncertainty space for the evaluation of the case studies. (Uniform U[lower;upper]; Normal N[μ;σ]; Halfnormal HN[μ;σ]; Gamma G[a;b])

Item	Value	Unit	Uncertainty	Source
Net Electricity Price (c_{el})	40.5	[€ MWh^{-1}]	N[40;3.5]	[114]
Electricity cost increase (j_{el})	2	[% p.a.]	U[1;3]	[114] [204]
PSO (c_{PSO})	33.5[1]	[€ MWh^{-1}]	HN[33.5;3.35]	[208]
Electricity Tax (heating) ($c_{\text{el, tax}}$)	27.0[2]	[€ MWh^{-1}]	HN[27.0;2.7]	[114]
TSO (c_{TSO})	9.86	[€ MWh^{-1}]	N[9.9;2.0]	[230]
DH Price (c_{DH})[3]	40.3	[€ MWh^{-1}]	N[40.3;4.0]	[231]
DH price increase (j_{DH})	0.9	[% p.a.]	U[-0.2;2.0]	[208]
DH tax rate winter	33	[%]	N[33;3.0]	[208]
WWT tax rate winter	0	[%]	G[2;1]	[208]
Value Energy Saving (c_{subsidy})	50	[€ MWh^{-1}]	U[40;60]	
Inflation	2	[% p.a.]	-	[114]
Discount Rate (d)	5	[% p.a.]	U[4;6]	
Profit share (S_P)	75	[%]	U[50;100]	

[1] Gradually phased out until 2022
[2] Until 2019 67.6 € MWh^{-1}
[3] Table shows average for Denmark. Real price are found for each DH area

Table 6.4: Summary of the model parameters for investment costs and their distribution in the input uncertainty space for the evaluation of the case studies. (Uniform U[lower;upper]; Gamma G[a;b]

Item	Value	Unit	Uncertainty	Source
Interest Rate (i)	10	[% p.a.]	U[8;12]	[173]
Loan Duration (N_L)	5	[years]	-	[173]
Equipment Lifetime (N_E)	20	[years]	G[2;1]	[188, 202]
DH Pipe DC	f(QDH)[1]	[€ kW^{-1}]	U[-20 %;20 %]	[187]
HP DC	675	[€ kW$_h^{-1}$]	U[550;800]	[202]
HP O&M	5.5	[€ kW$_h^{-1}$ year^{-1}]	U[4.5;6.5]	[202]
HEX DC	200	[€ m^{-2}]	U[150;250]	[202]
HEX O&M	2	[€ kW$_h^{-1}$ year^{-1}]	U[1.5;2.5]	[202]
ORC DC	1600	[€ kW$_{el}^{-1}$]	U[1300;1900]	[224, 232]
ORC O&M	35	[€ kW$_{el}^{-1}$ year^{-1}]	U[30;40]	[224]
Indirect Costs (of DC)	50	[%]	U[25;75]	[21]

[1] Specific investment costs for DH piping were found as a function of the delivered heat

Taxes and subsidies

In this work the applicable taxes on EH utilisation and electricity for EH recovery were considered, which depend on the excess heat sources and utilisation technologies. For each of the considered pathways in the model a brief overview is given for the Danish legislation based on [233, 234]. Danish companies are generally obliged to pay a tax on utilised excess heat when the heat comes from a process and is used by a special installation for a non-process purpose. The tax on surplus heat can originate in the legislation, regulating the taxation of energy for process and non-process purposes. The aim of the Danish surplus heat tax is to secure that no speculation is made in order to avoid paying similar energy tax for similar energy uses. The tax on surplus heat is put in place to compensate for a missing tax payment when process excess heat subsequently is used for a higher tax category as e.g. space heating.

With respect to the chosen cases in this work, the EH sources are process heat, utility systems and waste water. The sources may be further utilised for space heating, hot water, process heating and electricity generation. Furthermore, only the case of external utilization was considered, excluding the possibility of process integration, meaning recovering the excess heat for the use on within the factory. The following taxes and subsidies were considered:

(i) Process heat for district heating (directly or via heat pump): If the excess heat is sold to a district heating company without using a heat pump, the payable tax is the difference of the space heating tax (6.75 €MWh^{-1}) and the process heat tax. The tax is however capped to be not higher than 33 % of the excess heat price paid by the district heating company. Furthermore, a tax reduction is obtainable when a heat pump is used. The taxable heat is then reduced to the difference of the excess heat and twice the electricity needed, meaning only the heat produced at the COP above 3 is taxed.

(ii) Electricity generated from excess heat: The electricity generated from excess heat has no energy tax, as it currently is for all fuels. There are environmental taxes (e.g. NOx and SOx) for burning of fuels though, which are not relevant in this work. Taxes only occur for the use of electricity and if the electricity is generated using renewable sources, tax credits of up to 20 €MWh^{-1} can be applicable.

(iii) Electricity tax for heat pumps using excess heat: A tax has to be paid on electricity used for space heating, which also applies to electricity used in the heat pump. This adds the Public Service Obligation (PSO), electricity tax for space heating and the fee for the Transmission System Operator (TSO) to the net electricity price. In the future these taxes will change. The Danish government decided to reduce the electricity tax for space heating gradually between 2019 and 2021 [235]. Furthermore, the PSO will be phased out until 2022 [208].

(iv) Subsidies for excess heat utilisation: For the consideration of national subsides, the sale of energy savings to utility companies was included where relevant. The obligation for energy savings for utility companies allows, for example industries, to sell their energy saving projects [211]. Based on market prices, the value of one MWh saved energy was chosen to be 54 €. This price depends on supply and demand, the utility company it is sold to, and at which time of the year the energy savings are offered on the market, thus resulting in an uncertainty, which was estimated to be +/- 15 %.

Economic evaluation and comparison

The economic evaluation was performed by using the unit costs of the heat supplied or electricity produced over the lifetime, the NPV and the IRR (Section 2.6). The calculation of these indicators included the investment costs I, the annual fixed and variable Operation & Maintenance (O&M) costs, $C_{f,\mathrm{OM}}$ and $C_{v,\mathrm{OM}}$, the annuities, eventual subsidies and the costs of energy (heat or electricity) recovered from the excess heat. Investment costs were found for each case study and included the DH pipes, heat exchangers, heat pumps, ORC and thermal energy storages if applicable. For the operation of the system the electricity prices for heat pumps were used, together with maintenance costs for HP, ORC and heat exchangers as described in the following section.

The private-economic investment calculation was performed from the viewpoint of the owner of the EH source. Here, the revenue for the sold heat was set at 85 % of the difference between average price in the specific DH area and the heating price of the EH source. The share of the revenue depends on negotiations between the excess heat owner and heat consumer. In general it was assumed that the investor into the equipment takes the higher risk and therefore receives a higher share of the revenues. For electricity generation the net electricity price was used.

6.2.5 Uncertainty and sensitivity analysis

To quantify the uncertainty of the model output, the Monte Carlo (MC) method was used [71].The sampling of the input space was performed with Latin hypercube sampling (LHS). The approach of this analysis was based on the work by Sin and Gernaey [72] and was described in Section 2.7. The quantification and representation of the input uncertainty is shown in Table 6.1, 6.3 and 6.4. In addition to these values, the available excess heat and operating hours were described with an uncertainty of ± 20 % of the base value with uniform distribution. The excess heat temperatures were varied with ± 20 K and the one of waste water with ± 4 K. In the results, the mean and standard deviation are reported. The model was simulated using 1500 samples, which yielded stable results considering the 34 input parameters. A more detailed analysis was made to take into account the dispersion of the model output, by graphically representing the data in box plots.

In order to identify the most important model input parameters, Morris Screening [78] and linear regression of the MC simulations were used for the sensitivity analysis. After evaluating different settings, the reported screenings were chosen to be 30 repetitions and 6 levels, which resulted in a perturbation factor of 0.6. To avoid type II errors, which occur when an important factor on the model output is not identified, the absolute mean of the distribution μ^* was used [67]. For the sensitivity analysis based on linear regression, the Standardized Regression Coefficient (SRC) was used [67, 82]. In order to apply this method, the R^2 of the linear regression model should be above 0.7, which indicates that the model could be sufficiently linearized [70].

6.3 Results

6.3.1 Geographical mapping

Figure 6.3 shows Denmark with the individual excess heat sources marked as a point layer and the sum of the excess heat in each Danish municipality indicated by a colour gradient. An overview of the data used can be obtained from this figure. It can be further seen that the highest excess heat potentials were found in Aalborg, Kalundborg and Fredericia, where energy intense industries are located. The greater Copenhagen area, located in the very east of Denmark, has a high density of sources, but a comparable low excess heat potential as there is no heavy industry.

6.3.2 Identification and analysis of recovery scenarios

Based on the overall mapping as shown in Section 6.3.1, six cases of EH sources were identified, which were used as case studies for further investigation. Figure 6.4 shows the excess heat sources and district heating areas for selected areas. The EH sources and heat sinks were chosen to present relevant scenarios for further discussion and four of them are based on previous works [215]. The six cases were used to investigate different EH sources and utilisation pathways. Cases 1, 2 and 4 show large excess heat sources from industrial processes near district heating areas. Case 3 shows an excess heat source from a WWT plant close a DH area and Case 5 shows a utility plant (WWT and power plant) close to an industrial site. Lastly, Case 6 shows several large excess heat sources, from the building material industry without a nearby heating area. The information which were extracted from the GIS data are shown in Table 6.5 for the EH sources and in Table 6.6 for the possible EH users. In the following, each study is further characterised in more detail with respect to the excess heat source and heating demand, as well as the economic potential for utilising the excess heat.

Case study 1

In the first case study, the supply of excess heat to a DH area was analysed, where the temperature level of the excess heat did not allow a direct heat exchange and thus a heat pump was required. The heat source considered was from a chemical plant, available from evaporation, compression and refrigeration processes [219]. Temperatures of these processes are relatively

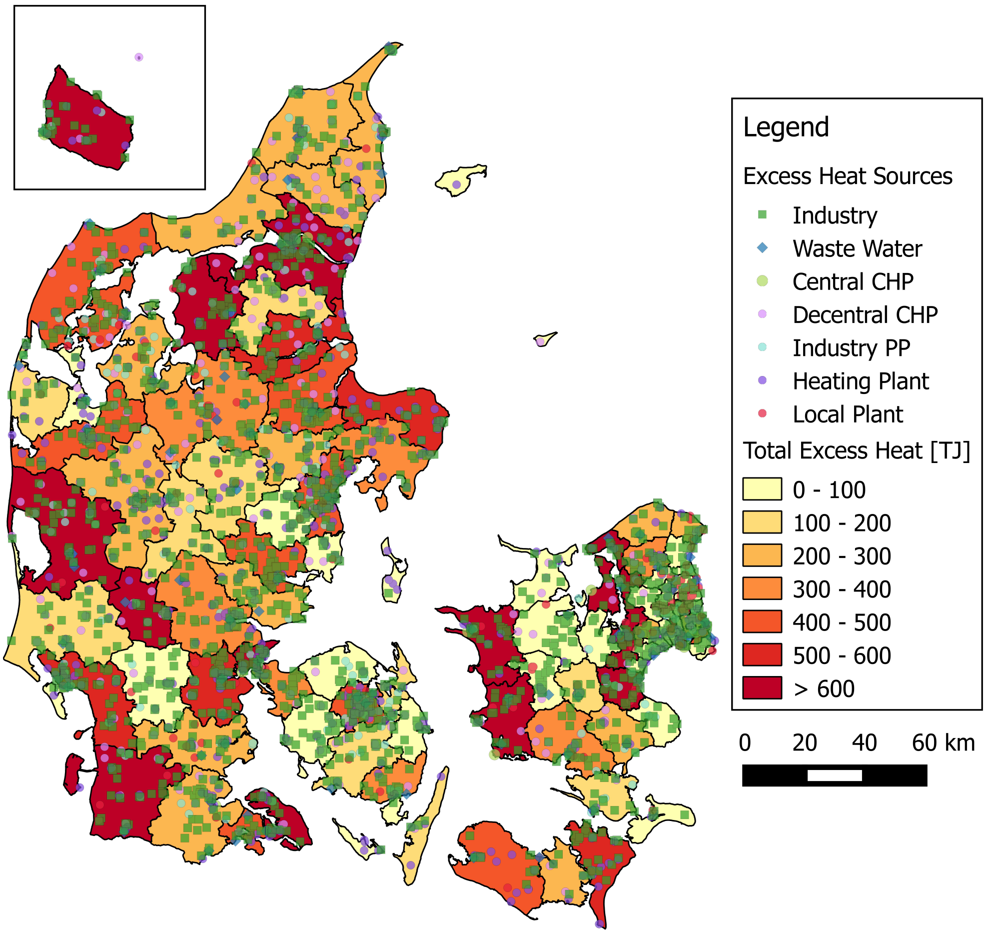


Figure 6.3: Map of Denmark with the location and type of the excess heat sources and the total sum of excess heat of each region.

Table 6.5: Overview of the data retrieved from, amongst others, the GIS model for the EH sources used in the case studies.

Case [-]	Source [-]	T_{EH} [°C]	Q_{EH} [TJ yr^{-1}]	Profile [-]
1	Chemical factory	80	10	PP1/3-shift
2	Metal factory	180	15	PP2/2-shift
3	WWT	14 -22	38	PP1/3-shift
4	Food factory	60	9.7	PP1/3-shift
5	Utility (Biogas)	110	15	PP1/3-shift
6	Brick factory	160	30	PP1/3-shift

low, in the range of 40 °C to 100 °C. For the specific case study an overall excess heat potential of 150 TJ per year was found based on the mapping. A detailed analysis of the source revealed

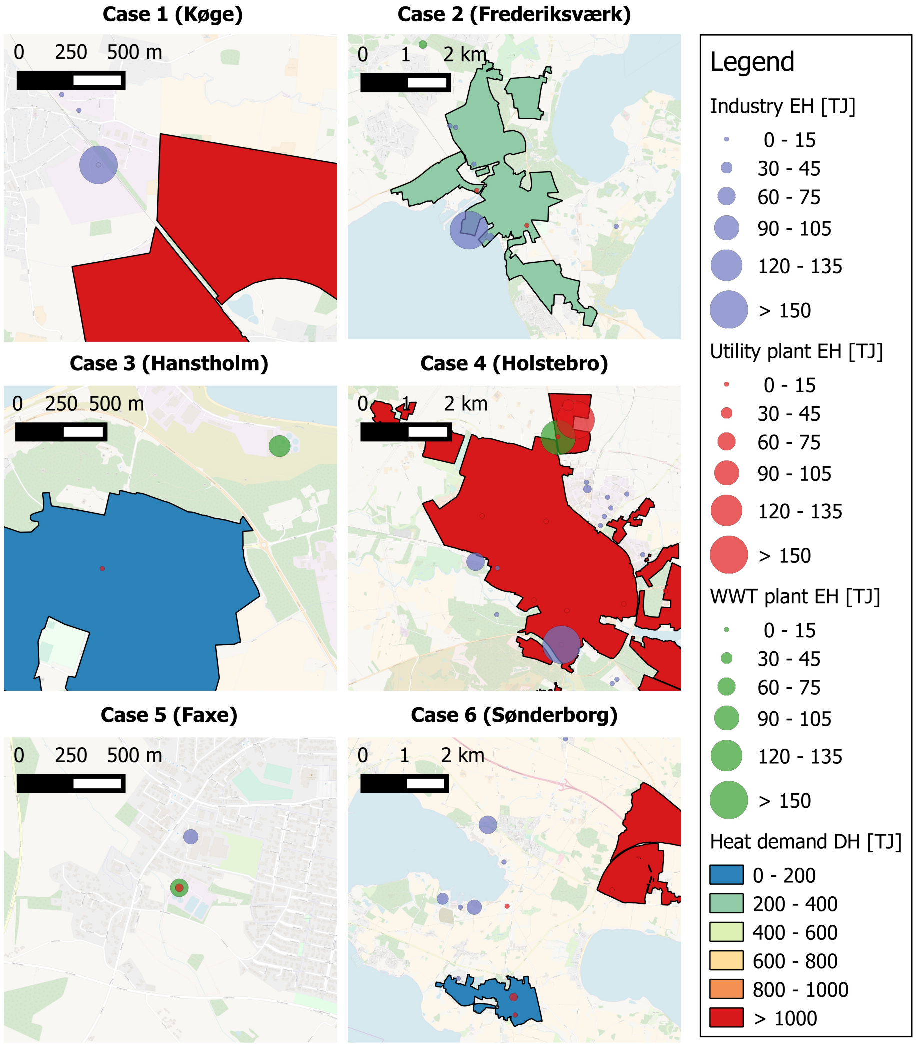


Figure 6.4: Examples of the identified case studies based on the overall mapping. The maps show excess heat sources as points with the radius of the points proportional to the annual excess heat. The locations of district heating areas are marked as polygons with the colour representing the annual heating demand.

that approximately 10 TJ were available at 80 °C from one distillation column on site. Furthermore, the production had 3 shifts and was considered evenly distributed throughout the year (PP1).

The heating demand of the local DH area (Køge bay area) was more than 9670 TJ per year with a supply temperature of 85 °C in winter. With the temperatures given in Table 6.5 and 6.6, values between 10 and 14 were achieved for the COP. The local DH area is connected to the Copenhagen DH network. A major part of this heat was supplied by central combined heat and power plants, of which 400 MW were from three politically prioritised waste incineration

Table 6.6: Overview of the data used for the EH users as analysed in the case studies.

Case [-]	Sink [-]	$T_{S,W}$/ $T_{R,W}$ [°C]	$T_{S,Su}$/ $T_{R,Su}$ [°C]	Q_{HD} [TJ yr^{-1}]	Profile [-]	L_{Pipe} [m]	Technology [-]
1	DH grid	85/ 47	75/ 55	9670	DH1	170	HP
2	DH grid	80/ 46	68/ 51	397	DH2	20	Direct
3	DH grid	73/ 39	69/ 43	110	DH2	410	HP
4	DH grid	77/ 38	67/ 42	14400	DH1	130	HP
5	Food factory	80/ 50	80/ 50	20	PP1/2-shift	150	Direct
6	Electricity	-	-	-	-	-	ORC

plants [236]. The choice of the district heating profile depends on the agreement found with the local authorities and how much of the existing summer capacity could be reduced. As the estimated excess heat source was small, compared to the total network capacity, the first district heating profile (DH1) was chosen.

Case study 2

The second case study analysed the supply of excess heat to a DH area, where the temperature level of the excess heat was sufficient to allow a direct heat exchange throughout the year. In the specific case, a metal processing industry was chosen, which lies within an existing DH area. In this industry the majority of the excess heat originated from heating, melting and compression. The current mapping estimated that more than 150 TJ of EH was available per year. The specific site manufactured steel plates, where a high share of thermal energy was used for the heating of the metal, before being formed. It was assumed that 15 TJ were accessible at a temperature of 180 °C. The local DH area of Frederiksværk had a heating demand of 397 TJ per year and, in winter, had a supply temperature of 80 °C. As it is a smaller DH area currently supplied by a biomass boiler (wood chips and pellets), the DH profile 1 was chosen. The steel plates were produced in three shifts and, to account for demand fluctuations, production profile PP2 was chosen.

Case study 3

In this case study a WWT plant is located in the vicinity of a small DH area. The WWT plant received residential sewage but to a large part also waste water from a neighbouring indoor fish farm. The temperature of the water leaving the WWT plant had varying temperature over the year. In Denmark this temperature typically varies between 10 °C and 20 °C [228]. For the analysis of the given case study, the temperature was varied over the four seasons using 10 °C for winter, 20 °C in summer and 15 °C in spring and autumn. This was a conservative estimate for this specific case - a more constant temperature than in other WWT plants could be expected, due to the high share of input of industrial waste water. The Hanstholm DH network had a comparable low supply temperature in winter of only 73 °C and was supplied by a biomass boiler, an electric boiler used for load balancing, an oil/ gas boiler with a HP for the exhaust gas and EH from a fish meal factory [237]. It was assumed that with the current supply in EH and from the electric boiler, the summer heating load was covered, thus the profile DH2 was chosen. The obtainable COPs for the heat pump were between 4.5 and 5.3.

Case study 4

This case study was similar to Case 1, where EH could be utilised with a HP for district heating. In this case the EH originated from a large site processing food, dairy products in particular, and was available at 60 °C in the exhaust gases of dryers. Other possible EH sources were available at the site, e.g. exhaust gases from the steam boilers and gas burners, as well as from refrigeration plants, which could also be taken into consideration. The production at the dairy site took place in 3 shifts evenly distributed over the year. The DH demand in Holstebro was covered primarily by a CHP plant using waste and biomass. For the DH temperatures given in Table 6.6, a COP of up to 10 could be expected.

Case study 5

The use of excess heat as a heat source for another industrial facility was analysed as part of the fifth case study. Here the industrial excess heat could be used as process heat, either through a heat pump or direct heat exchange. A possible scenario was found in the mapping, where up to 50 TJ of excess heat was available from the food industry and around 65 TJ from a waste water treatment plant. The WWT had a biogas engine which produces heat and power for internal use. The engine had a capacity of approximately 0.5 MW_e and 10 MW_{th}. As there was no existing larger DH area, the excess heat could be used for local industries.
The site for the food production had an estimated heating demand of 20 TJ in the temperature range of 80 °C for heating and cooking, following a two shift operation and production profile PP1. The excess heat from the biogas engine at a WWT plant was found to be at 110 °C based on the GIS model with an accessible potential of 15 TJ per year.

Case study 6

The use of industrial excess heat in cases where no heat demand is available and excess heat temperatures are high enough to generate electricity was considered in the sixth case study. The mapping identified an area west of Sønderborg, where several industries producing building material are located. These industries were not in the vicinity of other major heating demands, such as the district heating areas of Sønderborg and Broager. The main products of the industrial sites were bricks and the excess heat from those was estimated to be 62 TJ, 56 TJ, 36 TJ and 12 TJ per year, respectively. As those industrial sites had similar processes, with comparable process heating demands, the exchange of heat between them was not possible. Furthermore, the closest district heating area was located more than 3 km away. In the production of bricks, the majority of excess heat originated from drying and furnaces. The exhaust gases in the brick production were typically found to range between 50 °C and 80 °C from the dryers and between 150 °C and 250 °C for the furnaces [238, 239]. Already installed heat recovery systems and the use of the kiln flue gases for the dryer, reduce possible process stream for further utilisation. The temperature of the furnace air was chosen at the lower end as 160 °C and the usable excess heat amount at 30 TJ.

6.3.3 Economic analysis

The main private-economic results and their uncertainties are summarised in Table 6.7 and 6.8 for each of the case studies. The table also includes the uncertainty of each value. All case studies, except Case 3, were profitable over the assumed 20 year life time. Case 1 and Case 4 had however a low IRR, only slightly above the discount rate. Taking into account the uncertainties, these two cases could also be unprofitable, as the standard deviation exceeded the positive NPV. Case 3 presented the highest investment costs, because a heat pump was required for a large low-temperature EH source.

Table 6.7: Economic results for the case studies with uncertainty (standard deviation of the MC simulations) in percent.

		Case 1	Case 2	Case 3
Investment costs	[k€]	235 ± 26%	174 ± 43%	2337 ± 38%
Total O&M	[k€ yr^{-1}]	12.1 ± 34%	1 ± 22%	390 ± 36%
Subsidy	[k€]	58 ± 28%	10 ± 381%	602 ± 34%
IRR	[%]	8 ± 88%	54 ± 45%	-
NPV	[k€]	88 ± 190%	1083 ± 32%	-1269 ± 171%

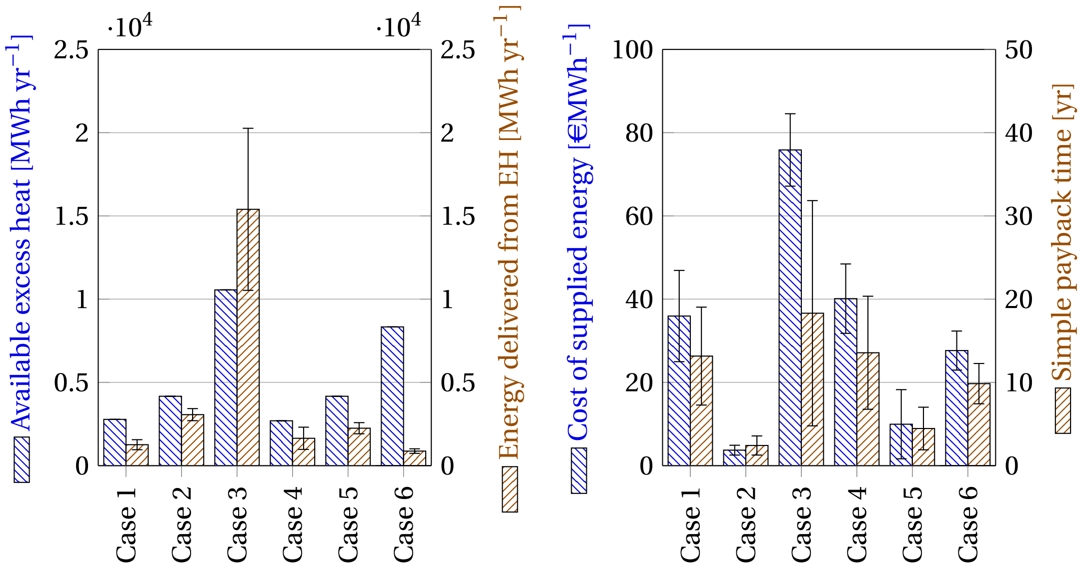
Table 6.8: Economic results for the case studies with uncertainty (standard deviation of the MC simulations) in percent.

		Case 4	Case 5	Case 6
Investment costs	2337 ± 38%	268 ± 40%	257 ± 40%	307 ± 27%
Total O&M	390 ± 36%	21 ± 57%	4 ± 158%	4 ± 21%
Subsidy	602 ± 34%	74 ± 41%	59 ± 93%	44 ± 19%
IRR	[%]	7 ± 92%	31 ± 44%	13 ± 27%
NPV	[k€]	37 ± 296%	810 ± 45%	283 ± 41%

In Figure 6.5 the case studies are compared by showing the available and recovered energy (Figure 6.5a) and their unit costs, as well as simple payback time of the investment (Figure 6.5b). Most cases could not recover the entire assumed EH, which was due to a limited demand

(Case 4) or due to remaining excess heat in the source (T_{min}).

The unit costs of industrial EH utilisation with a heat pump were less than 40 € per MWh and considerably higher than for the direct utilisation (Case 2). The heating price of utilising waste water for district heating, had a high heating price of 76 € per MWh, with a low relative uncertainty. For the given Case study 3, this investment would only be acceptable if the lifetime was high (above 20 years) and no cheaper renewable heat sources were available in the given heating area. The presented simple payback time only took into account economic feasible investment (revenues larger than the operating costs) obtained in the MC simulations and could thus only be meaningful in combination with the other indicators. Though the mean simple payback times were generally below 20 years, they were often too high for private economic investments where payback times of under 5 years are required.



(a) Energy indicators (b) Economic indicators

Figure 6.5: Main results with the standard deviation as uncertainty range.

Case study 6, where electricity was generated from EH, had a low unit cost compared to the net electricity price. The NPV over 20 years was with 283 k€ relatively low, but the uncertainty of the IRR and the other indicators were acceptable. In case study 3, the reason for the increased uncertainty was that the uncertainty of the excess heat temperature of the gaseous source in some uncertainty estimations caused the use of a heat pump, which had a great impact on the heat delivered, investment costs and operating costs. This was also shown in the sensitivity analysis, where the excess heat temperature for Case 3 had an over proportional influence.

Figure 6.6 shows the box plot of the costs for the supplied energy for each case. The bottom and top of each box represent the first and third quartiles of the distribution respectively. The whiskers extend to represent the values which fell within 1.5 times the interquartile range (third minus the first quartile). For Case 1 it can be observed that almost 75 % of the lowest MC simulations fell below the average DH price of 40.5 € per MWh. This suggests with a high certainty, that the heat from the EH source could be supplied at costs lower than the current ones. A more detailed analysis of Case 1 is thus justified.

Case 5 had a very uneven distribution of the MC simulations, with the median value being very close to the first quartile. There was furthermore a large dispersion of the possible costs in the upper half of the data. The main reason for this was the criteria for the subsidy, which should not bring the simple payback time below one year. As Case 5 had a good economy, it often did not qualify for the subsidy in the simulations. However, as soon as it qualified for the subsidy, the uncertainty of the parameters used to calculate the subsidy was added. Thus the higher costs of supplied energy were more scattered. The lower and upper ranges encompass considerable larger ranges than indicated by the standard deviations shown in Figure 6.5b. For Case 6 the highest outlier is in the same range as for Case 5, which was not obvious from the standard deviations. When comparing the spread of the values, as shown in the box plots, a better comparison of different alternatives would be possible.

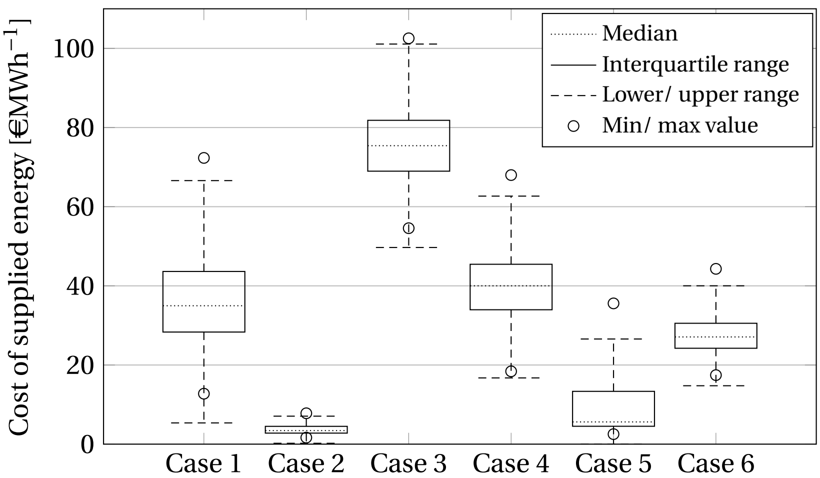


Figure 6.6: Box plot showing the costs for supplied energy for each case study.

6.3.4 Sensitivity analysis

The NPV was chosen as the model output to analyse the impact of the uncertain parameters, as the calculation of the NPV included all of them. Based on the two methods described in subsection 6.2.5, linear regression and Morris Screening, a ranking of the most influential parameters was performed. The sensitivity indicators, absolute SRC and μ^*, are presented in Table 6.9, 6.10 and 6.11 for the respective 5 highest scoring parameters. The R^2 values for the linearisation of the MC simulations were between 0.75 and 0.95 indicating that sufficient linearisation was possible to use the results.

This ranking reveals that all cases generating district heat had the district heating price, increase in DH price and profit share between EH emitter and DH operator as very influential parameters. In the ORC case, the electricity price and electricity price increase were determined as the most important parameter. These parameters all had a direct impact on the NPV and were identified as important using both sensitivity methods. In Case study 1 and 5 the excess heat temperature was identified as another important parameter, as it decided in these cases if a HP was required for the utilisation. On the other hand, in Case 3 the heat pump efficiency was important. Here the COP was low and thus the efficiency had a high impact on the electric energy use.

Table 6.9: Parameter significance ranking using linear regression of the MC simulations and the Morris Screening the NPV of case studies 1 and 2.

Rank	Case 1		Case 2	
	SRC	μ^*	SRC	μ^*
1	Profit share (0.60)	c_{DH} (0.68)	Profit share (0.71)	c_{DH} (0.72)
2	T_{EH} (0.49)	Profit share (0.63)	Q_{EH} (0.36)	Profit share (0.70)
3	c_{DH} (0.31)	T_{EH} (0.38)	c_{DH} (0.36)	n (0.41)
4	j_{DH} (0.19)	n (0.25)	j_{DH} (0.22)	Q_{EH} (0.33)
5	h_{EH} (0.17)	j_{DH} (0.21)	d (0.20)	j_{DH} (0.22)

Table 6.10: Parameter significance ranking using linear regression of the MC simulations and the Morris Screening the NPV of case studies 3 and 4.

Rank	Case 3		Case 4	
	SRC	μ^*	SRC	μ^*
1	Profit share (0.68)	Profit share (0.63)	Profit share (0.65)	Profit share (0.63)
2	c_{DH} (0.35)	c_{DH} (0.62)	c_{DH} (0.33)	c_{DH} (0.63)
3	η_{HP} (0.33)	η_{HP} (0.30)	j_{DH} (0.21)	T_{EH} (0.35)
4	j_{DH} (0.20)	T_{EH} (0.20)	T_{EH} (0.20)	n (0.21)
5	h_{EH} (0.17)	j_{DH} (0.20)	Indirect Costs (0.18)	j_{DH} (0.20)

To analyse the significance of the parameters on the costs of supplied energy and present more parameters, the results of the Morris Screening are shown graphically in Figure 6.7 for each case. The lines in each graph represent the mean value +/- the standard deviation divided by the square root of the repetitions [81]. Points lying outside of the lines have significant impact on the output. If the points are to the right of the curve, they increase the value of the results and vice versa. Parameters with a high absolute mean value have a high significance for the model, whereas a high standard deviation represents high interactions of the parameter. For Case 1 to 5, the EH temperature and the heat pump efficiency or heat transfer coefficient had a

Table 6.11: Parameter significance ranking using linear regression of the MC simulations and the Morris Screening for the NPV of case studies 5 and 6.

Rank	Case 5		Case 6	
	SRC	μ^*	SRC	μ^*
1	Profit share (0.60)	c_{DH} (0.60)	c_{el} (0.46)	c_{el} (0.78)
2	T_{EH} (0.49)	Profit share (0.57)	h_{EH} (0.42	n (0.52)
3	c_{DH} (0.31)	T_{EH} (0.44)	ORC DC (0.32)	h_{EH} (0.32)
4	Q_{EH} (0.27)	n (0.32)	j_{el} (0.28)	d (0.26)
5	j_{DH} (0.19)	Q_{EH} (0.23)	d (0.30)	j_{el} (0.25)

high mean and standard deviation. The minimum temperature differences could have a high impact if the system requires a heat pump, then also the costs related to the electricity were important. The variations of the value for the sale of energy savings, as part of the subsidy had usually no impact on the result. For the ORC case (Case 6), the main influential factors were the annual operating hours, lifetime and costs directly related to the ORC investment.

6.3.5 Environmental considerations

The data implemented in the GIS model further allowed an evaluation of potential conflicts with current heat producers and environmental benefits. An example of the possibilities is given in the following for the first two cases.

The proposed match in Case 1 would supply heat to the greater Copenhagen district heating network. Currently the network is supplied by heat from several central combined heat and power plants, which are using biomass (wood chips and pellets) or are in the transition of replacing coal with biomass. The delivered district heat from the chemical plant was found to decrease the heat supply from existing sources by less than 0.2 %, having negligible influence on the power production.

For Case study 2, the current district heating demand was covered by 84 % of wood chips, 13 % natural gas and 3 % bio oil fired in one heating plant. Substituting some of these fuels would thus not impact electricity production. Carbon emissions would not be reduced significantly as the majority of the district heat is supplied from biomass and the excess heat originates from burned natural gas.

6.4 Discussion

The excess heat used for the geographical mapping was based on aggregated numbers, which were distributed to sites and grouped excess heat from different sources. The excess heat found for a given point may thus originate from multiple sources. It is thus necessary to

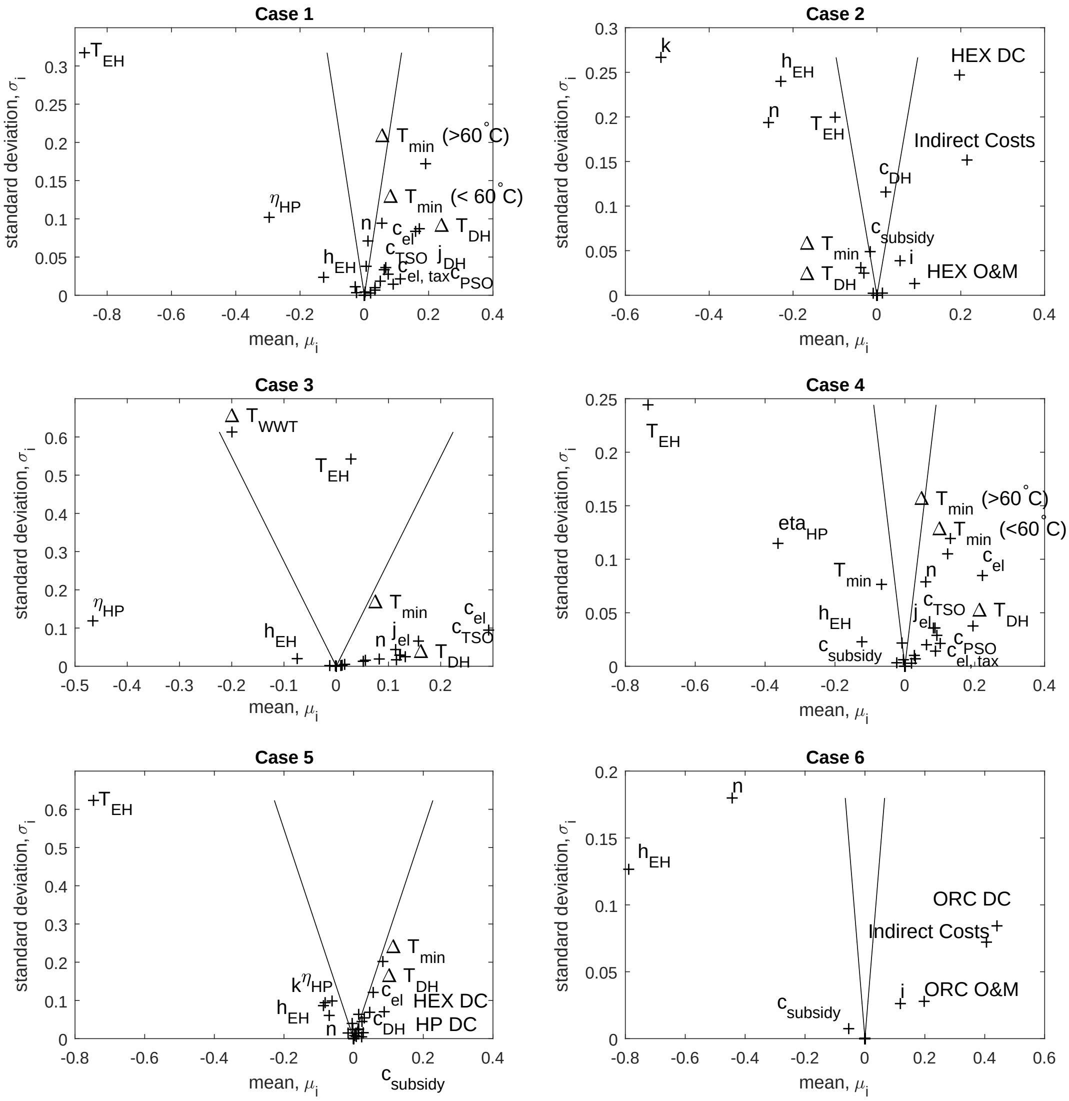


Figure 6.7: Results of the Morris Screening for the most important parameters influencing the costs of supplied energy (c_H).

carefully analyse any match and the near vicinity of the point sources to determine the real potential of excess heat and heating demand for any match. Information from the literature can be used in a first estimate to describe the excess heat sources. It should further be carefully evaluated if there are any opportunities for heat integration on site or reduction of the excess heat by improved equipment and process control, as this would be favoured to an external utilisation. This aspect was not included in the present study, but it was assumed that an internal assessment has already been made or would be made prior to performing a detailed feasibility study.

Several studies identified large technical potentials for the external utilization of excess heat.

These potential mainly refer to DH and some potential for electricity generation. However, these potentials are not realized, i.e. excess heat constitutes only 2 % of Danish district heating production. One of the main reasons for this gap is the lack of business models and common practice. The common practices keep industries and district heating companies within their core business areas, i.e. investing into known technologies (e.g. DH boilers). At the same time, the external utilisation of excess heat could be the most beneficial for both sides.

For the economic analysis key figures were used to estimate the costs for the given system, without performing a detailed technical evaluation of component sizes and their costs. The economic evaluation was performed to give a quick overview of the feasibility and should be able to be applied to a large number of cases without having to specify additional parameters than the ones found in this work or general literature. If a match is assessed as feasible with the given uncertainties, a more detailed evaluation has to be undertaken. This evaluation should also include the necessity of using thermal storage tanks for daily load and demand variations, a detailed analysis of the processes on site and how the excess heat can be utilised. The sensitivity analysis shows further the most important parameters, for which the quantification should be made with care. These are, besides the investment costs and heat pump efficiency, the annual operating hours, accessible excess heat amount and temperature. The substitution price depends on the local energy network and, together with the agreements between the owner of the excess heat and the utility company, has an impact on the final economic outcome. If the utilization of excess heat proves to be economically feasible, the open question is how the profit should be split. In the present tool, the assumption is that the industrial plant will take 75 %, while the district heating company will take 25 % of the profit. In reality, this will be the result of negotiations of the two sides.

A comparison of the costs with other literature values, show that the assumptions and order of magnitude of the results in this work are comparable. Karner et al. [177] found, for two case studies in Austria, costs for urban heating from industrial excess heat between 27 and 38 € per MWh and average amortization times of 7 years. Eriksson et al. [217] found a heat sale price of 20 € per MWh for a case in Sweden. In Denmark, several projects are documented where DH is supplied by large heat pumps [240]. For the combined supply of DH and cooling, heating costs of 55 € per MWh (simple payback time of 4.6 years) in one project and 47 € per MWh (simple payback time below 3 years) in another one were obtained. A price of 30 € per MWh was given to another project, where industrial EH is used for DH. These costs for EH utilisation are comparable to the ones found in this work, but also show the large variations which arise from different characteristics of each case. There is thus a necessity for an initial evaluation and comparison of possible cases, taking the most important characteristics into account. Considering this, the presented tool will allow the managers of DH companies and industries to analyse potential synergies, i.e. allowing DH companies and industries to become aware of the cooperation possibilities. If the cooperation proves to be economically feasible (low payback time) with acceptable uncertainty, a detailed analysis should be conducted. If the calculated uncertainty is too high, the cases could be re-evaluated using the tool but with more robust input parameters. If the economic indicators are poor, there is no need for additional analyses.

In order to improve the model output, the profit share between the EH emitter and the EH user needs to be more certain, as it has a high impact on the overall evaluation. By creating generally applicable business models or referring to previous accomplished cases, this value can be refined but will still depend on final negotiations. Though the DH price in a given DH area is known, the substitution price might be different or change with future investments. The EH temperature needs to be carefully chosen, in particular when it is close to the heating demand temperature, as small differences will impact the requirement of a heat pump and thus the investment and operating costs.

6.5 Conclusion

This work presented a method to identify, analyse and evaluate cases for utilising excess heat. The method is based on a geographical mapping in GIS, where excess heat sources from the industry and utility sector, as well as heating demands are shown. The GIS mapping was used to identify specific cases where excess heat could be utilised externally for heating purposes or electricity production. Using a developed model for a fast economic and technical evaluation of potential matches, the feasibility of the matches was evaluated. The approach of using the GIS model in combination with economic and technical analysis is suitable to identify local synergies. This has a particular relevance for energy planners, DH operators and industry representatives, who get the possibility to analyse investment opportunities with readily available data and first assumptions.

In the second step an uncertainty and sensitivity analysis was performed for each case, which can be used to better assess the model results and refine the input data and assumptions. The six case studies evaluated in this chapter considered industrial EH and waste water for district heating, as well as EH from a utility to an industrial plant and lastly industrial EH for electricity generation. It was shown that the costs of the supplied heat were below the average DH prices, except for the EH from WWT. The IRR for the feasible cases ranged from 7 % to 54 % and depended considerable whether a heat pump was used or not. The reported uncertainties of the mean values, found with the Monte Carlo method, show an acceptable uncertainty which allows a first decision on the projects feasibility. The sensitivity analyses identified several critical parameters, which must be carefully chosen. The price obtainable for the generated heat, as well as the share of the profit between the EH emitter and the owner of the heat demand has a great influence one the projects economy (i.e. IRR and NPV). A detailed evaluation of possible business models for synergies is required, which would reduce uncertainty of these values before detailed negotiations. The costs of the recovered heat are primarily influenced by the excess heat temperature. In particular when the required sink temperature is close to the EH temperature, the uncertainty increases, as the use of a heat pump might be required with corresponding increases in cost.

7 Methods for the analysis of industrial sites: The case of a dairy factory

In this chapter, different methods for analysing the performance of thermal systems are applied to an industrial process and their outcomes are compared. The selected case study is a Danish milk powder production factory which was first modelled and then analysed using engineering, pinch and exergy methods.

7.1 Introduction

Increasing the energy efficiency of the manufacturing industry has the potential to significantly reduce the greenhouse gas emissions caused by burning of fossil fuels and the operating costs associated with energy use. The production of dairy products is an important industry in Denmark and Europe and represents one of the most energy-intensive industries within the food sector [241]. In Denmark, 20 % of the agricultural exports are dairy products and a total of 4.7 billion kg of raw milk are processed, resulting in export revenues of 1.8 billion Euro [242]. For the determination, quantification and prioritisation of possible energy savings in complex and large-scale industrial sites, several scientific and engineering methods exist and are under continuous development. The potential for increasing the energy efficiency of the dairy production processes, which are often already highly integrated, still exists. As shown by Ramirez et al. [241], the energy use per amount of final dairy product has steadily decreased in France, Germany, the Netherlands and UK. Also large differences were observed amongst countries, indicating that a more energy efficient production is possible. Masanet et al. [243] further shows several energy efficiency opportunities which could be considered to be implemented in dairy factories. The aim of the present chapter was to identify this potential by applying and assessing different methods and is based on [244], [P7] and [C5]. The methods used were based on energy analysis, pinch analysis, exergy and advanced exergy analysis.

7.1.1 Literature review

Van Gool [245] investigated the use of exergy in the design and analysis of industrial processes, also comparing the exergy method to conventional thermodynamic analyses. The discussion implies that exergy analysis in the design of a process often shows losses already known. However, exergy analysis also determines the efficiency of the process, which in combination with the losses determine the potential for improvement. The work by McKenna [246] analysed a glass furnace using energy and exergy analysis and a mechanical paper making process using pinch analysis. The discussion of the methodologies shows that the energy system often determines the applicable methodology. In the case of exergy analysis it was possible to differentiate between exergy losses and destruction, as well as highlight the areas on which to focus for improvements. These focus areas were however similar to the ones obtained from the energy analysis. One important issue raised by McKenna [246] was the high share of unavoidable exergy destruction in many processes, such as combustion, which resulted in low exergy efficiencies.

For the dairy industry in particular, several studies were conducted in the last decade. However, these studies primarily analysed the milk processing [247, 248] or only the drying process [249]. Quijera and Labidi [247] and Quijera et al. [250] use the pinch and exergy methods to evaluate and optimise the integration of solar thermal technologies for the production of cheese and yoghurt. An exergy analysis for the pasteurisation of milk was performed by Fang et al. [248], where the process was also optimised. Most recently, Yildirim and Genc [251] performed an exergy analysis of a milk powder production system, consisting of a single stage evaporator and a spray dryer. Srinivasan et al. [252] analysed an Indian milk powder plant using exergy analysis with the main aim being a comparison of two energy efficiency scenarios. The suggested energy efficiency measures increased the exergy efficiency of the overall system, in particular the pre-heaters were improved. The usefulness of exergy as a tool for the dairy industry was discussed by Vidal et al. [253]. A milk powder production facility in New Zealand was analysed for this purpose to investigate the usefulness of exergy methods in the dairy industry. Based on component-wise product input/output states an exergy analysis was conducted and the authors concluded that exergy might be useful to design and optimize different units of operations within dairy processes. The exergy losses of flavoured yoghurt production were determined by Sorgüven and Özilgen [254], and the production of other ingredients than milk were also included from a cumulative exergy perspective.

Several exergy analyses were conducted for different systems within the food industry and a study by Trägårdh [255] used exergy as a quality factor. Most relevant for this work were articles on drying and evaporation technologies, such as Marnoch et al. [256] who performed an exergy analysis of broccoli drying. A review of exergy analyses of drying processes was done by Aghbashlo et al. [257]. Evaporation in food processes was discussed by Leo [258] for the processing of citrus fruits. Balkan et al. [259] analysed a three-effect evaporator for fruit juice processing applying exergy analysis. Winchester [260] analysed the modelling and operation of falling film evaporators at the example of a dairy plant. Most recently Zhang et al.

[261] compared a five-effect evaporator to a three-effect evaporator with mechanical vapour re-compression for milk concentration. The latter only used one third of the energy compared to the conventional five-effect one. Much of the literature on evaporation with thermal and mechanical vapour re-compression technologies focused on sea water desalination. For instance Choi et al. [262] did an exergy analysis of thermal vapour re-compression evaporators, suggesting new designs and operating parameters.

The exergy destruction occurring in a given component depends on its characteristics and is also impacted by the performance of the other components present in the system. The common exergy analysis has some barriers to show the real recoverable losses, which can be identified by an advanced exergy analysis [55, 263]. The method of advanced exergy analysis is well-documented and has been applied to several systems, such as refrigeration machines [56] and combined cycle power plants [264]. The application of advanced and conventional exergy analyses to an industrial plant was conducted in one study [58, 265] for the production of rubber. These analyses document the usefulness of carrying out an advanced exergy analyses, as the improvement priorities can be ranked based on exergy destruction.

The published works until now have shown that the application of different methods for analysing industrial processes, components and utilities can reveal optimisation potentials and allows the comparison of different alternatives. However, it is also noted in the literature that many of these advanced methods are not applied in industrial practice. Rosen [18] states that exergy is often not utilised in industry as the method may be considered inconvenient or complex and the results as difficult to interpret and utilize. An overview of the application of possible methods and a comparison of the outcomes, would give a better understanding of the practical applicability of the methods for process analysis and additional information which could be obtained compared to normal engineering methods. For dairy production systems in particular, several analyses have been performed in the past as shown above. No study applied advanced exergy analysis on a food production processes, nor where the interactions between the utility systems and the production system analysed using advanced thermodynamic methods. Investigating these relations would give additional insights in the process, optimisation opportunities and present a basis for changes in the utility systems.

7.1.2 Aim

The aims of this study were to: (i) determine the potential for improving energy use and inefficiencies of an integrated milk powder production line using energy and exergy methods, (ii) study the interactions of the system by applying the concept of advanced exergy analysis and (iii) compare the different methods for the analysis of inefficiencies and potentials for improvement in industrial processes. The focus was the application of exergy and advanced exergy methods, while comparing the results to energy analyses applied in the consultancy and process integration. The conclusions drawn from the different analyses were compared, including a discussion of the applicability of the exergy methods to industrial processes and pinpointing challenges occurring in their application. The comparison was performed qualitatively, based on the required modelling effort, level of detail, assumptions, experience and the main improvement suggestions obtained from each method. The chapter is based on [244, 266].

This chapter is organised as follows. First the case study and the approaches for modelling the dairy system are introduced in Section 7.2.1. This is followed by an introduction to the applied methods (Section 7.2.2), complementing the methods presented in Chapter 2. The results of the analyses and the comparison of methods is presented in Section 7.3. Finally the methodologies are compared in the discussion and conclusions are drawn. Increasing the energy efficiency of the industrial sector has the potential to significantly reduce the greenhouse gas emissions associated with the consumption of fossil fuels and the operating costs associated with energy use.

7.1.3 Dairy industry

There are a number of dairy products, all requiring a different degree of processing. The overview by Ramirez et al. [241], showed that the fresh milk products only require heating, cooling and separation processes. More complex processes are required for the production of milk, whey or protein powders. For these also evaporation, mixing and drying processes are required. In the EU28 around 2800 thousand tonnes of milk powder were produced in 2016, of which 129 thousand tonnes came from Denmark [267]. This was equivalent to approximately 3 % of the total raw milk production. The production of milk powder had however a ten time higher specific energy use than liquid milk products [241], which accounted for 30 % of the products. Developing countries have an even higher motivation to reduce the energy use in their dairy production. In Brazil more than 85 % of the thermal energy originated from firewood and 84 % of the power from Diesel engines [268]

A detailed description of the procedures, processes and technologies in dairy processing can be found in the literature [269, 270]. An overview of the processes for milk powder production is given in the following.

Milk powder production

The incoming raw milk from the farm is first separated into cream and skim milk and then thermally treated (pasteurisation). In some cases, a fraction of the skim milk is passed through a reverse osmosis system, where water is removed. The milk, retentate from the reverse osmosis and additives (e.g. vegetable oil and sugar) are mixed, thermally treated and homogenised before being passed on to the evaporation section. Here, water is removed from the milk mixture by means of evaporation. The dry matter content is increased from between the mixture having 10 % to 12 % to the concentrate between 48 % and 60 %. The concentrate is then passed on to the spray dryer, where the remaining water is removed with hot air. The finished product has a dry matter content of above 95 %.

Milk treatment and separation The raw milk needs to be thermally treated to eliminate the pathogenic and other micro-organisms. To kill the most resistant bacteria contained in milk, the raw milk needs to be heated to 63 °C for 10 minutes [270]. The level of thermal treatment depends on the final product and usually ranges from 72 °C for high temperature pasteurisation to 140 °C for flow sterilisation. Centrifugal separators are used to separate cream from milk and to standardise the products with respect to fat and solid content. In the homogenisation step, the fat globules are disrupted into much smaller ones. These are standard processes in the liquid milk section and are performed, amongst others, before the evaporation.

Evaporation Within in the dairy industry falling film evaporators are used to evaporate water from the milk [269]. This type of evaporator is designed as shell and tube heat exchanger and has a separator for the concentrate and vapour. Some ingredients in the milk, i.e. proteins, are heat sensitive and undergo denaturation at the boiling point at ambient temperature. The evaporation therefore occurs at lower temperatures, which requires a vacuum.

Two types of evaporator configuration are generally used to reduce the energy use. The mechanical vapour re-compression (MVR) is used extensively in the dairy industry, where a fast revolving high-pressure fan capable of operating under vacuum compresses the product vapour in order to re-use the latent heat from the evaporated liquid. The thermal vapour re-compression (TVR) uses high-pressure steam in an ejector to raise the temperature and pressure of the vapour.

After the evaporation the milk concentrate has a dry matter content of between 45 and 55 %. The condensate from the evaporation process is often used to preheat the incoming milk.

Drying The drying section follows the evaporation processes. At first, the milk concentrate is heated to 70 °C to 75 °C. The spray dryer is the first step. Spray drying is a suspended particle processing system, it breaks down the liquid particles, through atomization, to create droplets which are dried to individual particles while moving in a gaseous drying medium. During spray drying the principles of convection drying are applicable, where the heat of vaporization for the droplet drying is supplied by the sensible heat of the drying air.

The powder collected at the bottom of the spray dryer is often passed through fluidised beds, which have the function to remove more water, regulate the temperature and guarantee a good consistency of the product.

The outcoming air of the different dryers is passed through cyclones to remove milk powder particles and feed them back to the product flows. The air is cleaned in a final step in a baghouse or wet scrubber, where remaining particles are removed.

Energy efficiency in the dairy industry The energy use in the major European dairy producing countries has decreased over two decades until 2001 [241]. There is a number of possible energy efficiency measures which can also be implemented by modern factories. Masanet et al. [243] presents several measures which can be applied to the production of different products and utility system. Their suggestions range from adding more plates to regenerative heat exchangers, multiple effect evaporators, membrane filtration for concentration and exhaust heat recovery from the drying air. For milk powder production, emerging technologies are summarised and evaluated by [271]. Membrane distillation, radio frequency heating, drying air dehumidification and contact sorption systems are stated as some possible technologies, but also solar thermal system to supply some of the required thermal energy.

7.2 Methods

In the following the methods applied in this work are described. The work is based on the modelling of a case study which is first introduced, together with the modelling approach and assumptions (Section 7.2.1). This is followed the description of the methods used for the case analysis (Section 7.2.2).

7.2.1 Case study and system modelling

The case study was conducted for a large dairy factory producing primarily milk powder. Both the production line and the utility system were included as shown schematically in Figure 7.1. The modelled milk processing line was part of several parallel production lines, representing all major production steps. The processing line consists of the following subsystems:

(i) Separation of raw milk into skimmed milk and cream alongside with thermal treatment of the two products (pasteurisation)

(ii) Mixing of skim milk with additives, homogenisation and high temperature treatment

(iii) Preheating of the mixture and evaporation of water in multi-effect evaporators

(iv) Drying of the milk concentrate in spray and fluidised bed dryers

Each subsection has fixed set points (temperature, pressure and dry matter content), and can be operated individually. The three first subsections are similar and are located in the same production unit, implying that the dairy factory can be split into three sections (milk treatment, evaporation and drying) which are used in the following.

Production

The studied milk processing system is shown schematically in Figure 7.2, where the main components and states are shown. The incoming raw milk is heated to the separation temperature

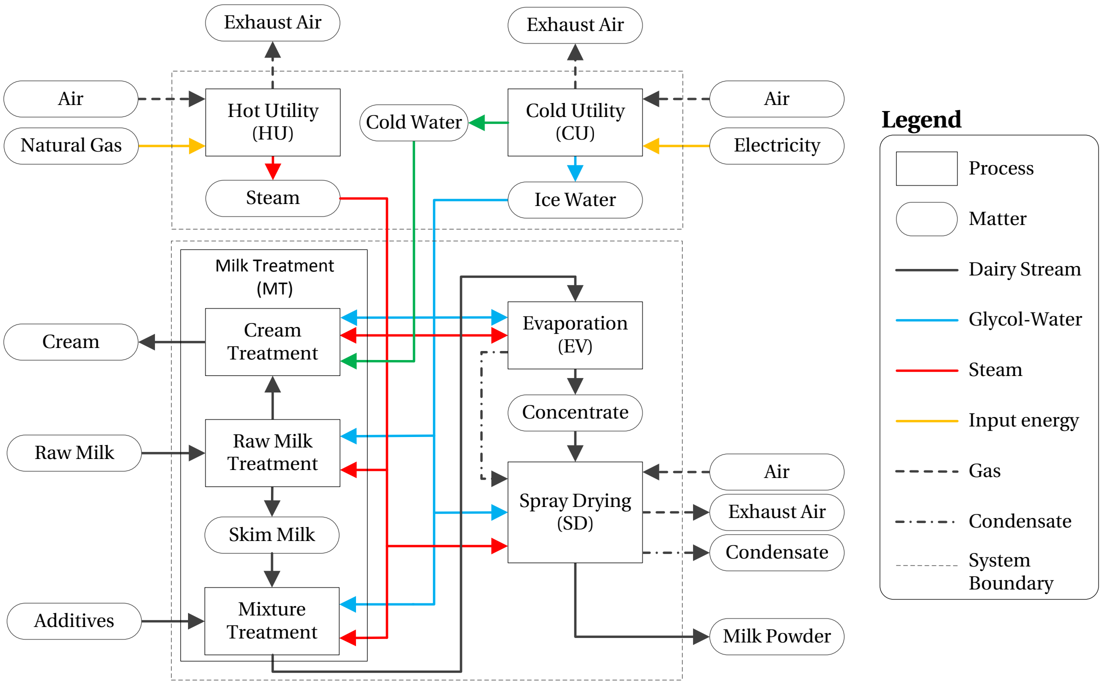


Figure 7.1: Dairy processing line for the production of milk powder with the main manufacturing units and materials.

at 50 °C, where the raw milk is separated into cream (C1) and skimmed milk (M3) by means of a centrifuge. The skimmed milk and cream are then pasteurised (at 75 °C and 85 °C, respectively) and cooled down to 5 °C, first by a regenerative heat exchanger and secondly with the cold utility. The skimmed milk is further enriched and standardised with additives (i.e. vegetable fats, sugars, vitamins and minerals). The resulting mixture is pasteurised and cooled down a second time. In the evaporation section (Fig. 7.3) the mixture is heated to up to 85 °C in one regenerative step and one with externally supplied heat. The evaporation of milk first takes place in one single stage evaporator with mechanical vapour re-compression (MVR) at 75 °C where the dry matter (DM) content is increased from 15 % to 35 %. The DM content is further increased to 52 % in one three-effect evaporator with thermal vapour re-compression (TVR) at an evaporation temperature of 67 °C in the first step. After the concentrate is preheated to 75 °C, it is injected into the spray dryer by an atomiser. The remaining water is removed in the spray drying system to achieve a DM content of 95 %, as shown in Fig. 7.4. The air for the spray dryer requires a temperature of 210 °C. This is achieved by first heating the air with condensate from the evaporators, followed by a steam heater. The powder leaving the spray dryer is further treated in an external fluidised bed dryer, where primarily the milk powder is cooled and correct product consistency is achieved. After the fluidised bed dryer a dry matter content of 97.5 % of the product is obtained. The drying air is filtered in a cyclone, to recover milk powder, and in a last stage in a bag filter before leaving the system.

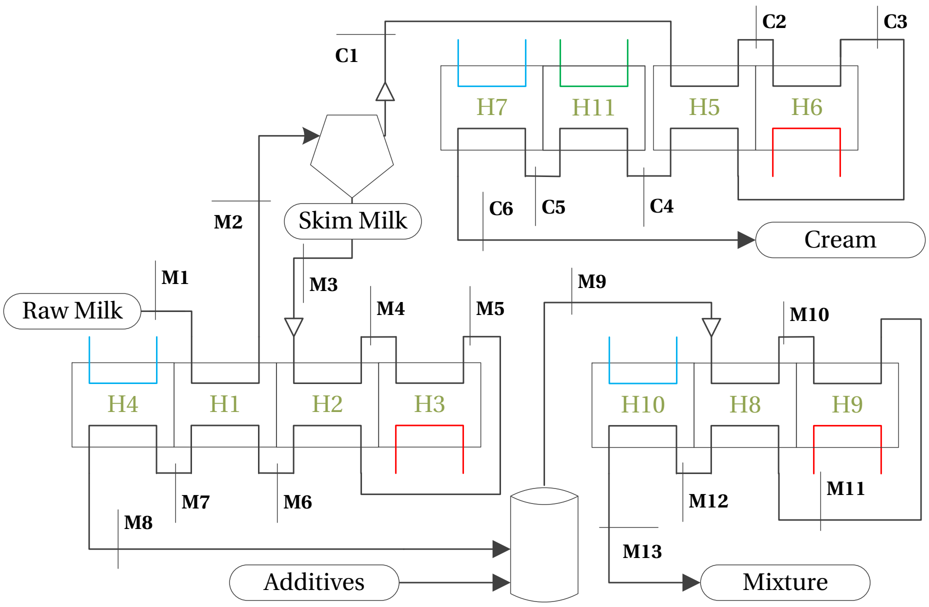


Figure 7.2: Milk treatment section for the pasteurisation, pre-concentration and mixing of milk and cream.

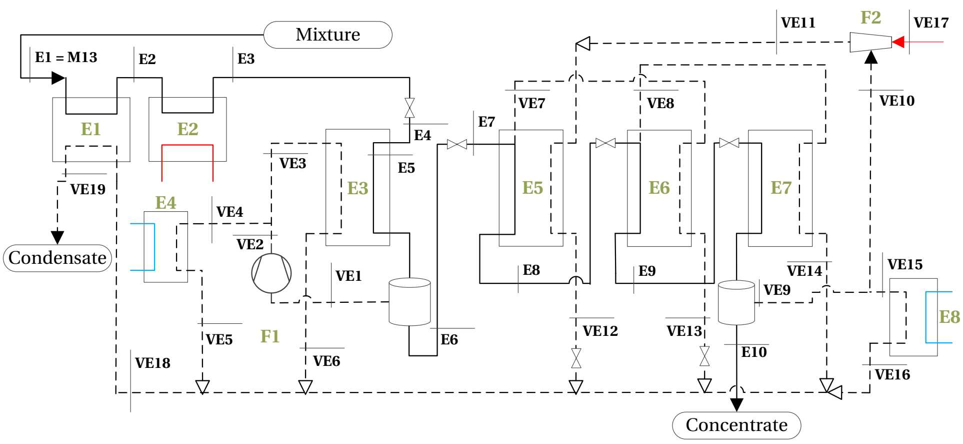


Figure 7.3: Evaporation section for the production of milk concentrate.

Utility

In addition to the production line the utility system is further included in the analysis. The heating demand is covered by steam at 25 bar supplied from a natural gas fired boiler (Fig. 7.5a). This pressure level is chosen to supply the highest temperature in the system with saturated steam. The combustion gases enter a boiler and are afterwards used to preheat the combustion air. Other systems may use the exhaust gases for feed- or makeup water preheating. The cooling demand is provided by ice water, an ethylene glycol-water mixture, with glycol content

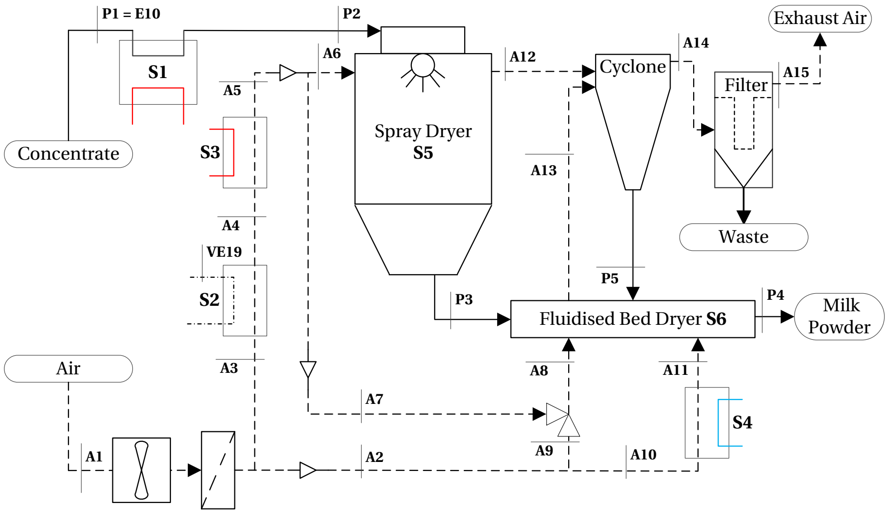
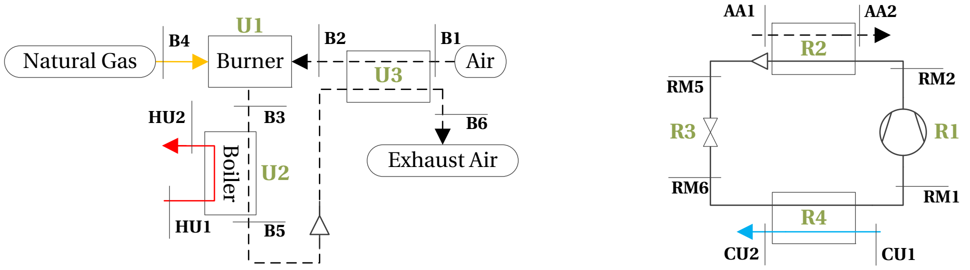


Figure 7.4: Drying section for the production of milk powder.



(a) Hot utility

(b) Cold utility

Figure 7.5: Natural gas boiler with economiser for the hot utility supply

of 30 %. The ice water is supplied by an ammonia refrigeration system, which can be seen in Fig. 7.5b. The set-point for the ice water is 2.5 °C. All state points of the utility can be found in Appendix B.

Model assumptions

The process modelling built upon the real operation parameters and conditions of the production line, as found in process data and from on-site measurements. The following assumptions were taken. The processing line produces different products that are pasteurised at different temperature levels, and they have varying dry matter contents after the mixing unit, depending on the milk additives. The input feed was modelled as a representative mixture with a composition corresponding to the use of skimmed milk and additives.

The number of evaporation steps in the MVR and TVR depends on the product mixture. In this work the most common set-up was chosen. It consists of a single-effect MVR and a three-effect TVR. The heat losses from heat exchangers and other process components were neglected. Further, start-up of the lines and cleaning in place (CIP) were not included. The reader is referred to [269] for a detailed technical description of the technologies and processes used in the production of milk powder. An extensive description of the evaporation with vapour compression in single and multiple stages for salt water desalination is found in [272].

The heat exchangers were modelled with energy balances, based on the streams inlet and outlet enthalpies and mass flow rates.

$$\dot{m}_{\mathrm{hot}}\left(h_{\mathrm{hot,in}} - h_{\mathrm{hot,out}}\right) = \dot{m}_{\mathrm{cold}}\left(h_{\mathrm{cold,out}} - h_{\mathrm{cold,in}}\right) \tag{7.1}$$

If a dairy stream was present at either side of the heat exchanger, the specific heat capacity of the milk was used, which was found as described in Section 7.2.1. For the pasteurisation, for example, the heat requirement was found as:

$$\dot{Q}_{\mathrm{milk}} = \dot{m}_{\mathrm{milk}}\frac{cp_{\mathrm{milk,in}} + cp_{\mathrm{milk,out}}}{2}\left(T_{\mathrm{milk,out}} - T_{\mathrm{milk,in}}\right) \tag{7.2}$$

The evaporators were modelled following Eq. 7.3, where the condensation of the steam takes place on the hot side.

$$\dot{m}_{\mathrm{hot}}\left(h_{\mathrm{hot,in}} - h_{\mathrm{hot,out}}\right) = \dot{m}_{\mathrm{conc,out}}h_{\mathrm{conc,out}} + \dot{m}_{\mathrm{vapour,out}}h_{\mathrm{vapour,out}} - \dot{m}_{\mathrm{conc,in}}h_{\mathrm{conc,in}} \tag{7.3}$$

The entrainment ratio for the ejector used in the TVR was found based on Granryd et al. [273].

$$\frac{\dot{m}_{\mathrm{VE,10}}}{\dot{m}_{\mathrm{VE,17}}} = \sqrt{\left(\eta_{\mathrm{N}}\eta_{\mathrm{D}}\right)\frac{\left(h_{\mathrm{VE17}} - h_{\mathrm{VE10,is}}\right)}{\left(h_{\mathrm{VE11,is}} - h_{\mathrm{VE10}}\right)}} - 1 \tag{7.4}$$

The isentropic efficiency of the compressors in this work was defined as in Eq. 7.5 at the example of the MVR.

$$\eta_{\mathrm{is}} = \frac{\left(h_{\mathrm{VE2,is}} - h_{\mathrm{VE1}}\right)}{\left(h_{\mathrm{VE2}} - h_{\mathrm{VE1}}\right)} \tag{7.5}$$

The air requirement for the spray dryer and fluidised beds were found based on the data from the factory. A fixed air to product ratio, AP, was used.

$$\dot{m}_{\mathrm{A16}} = \dot{m}_{\mathrm{P3}}\mathrm{AP} \tag{7.6}$$

The burner U1 in the hot utility was modelled by assuming a complete combustion of methane with excess air as shown in the stoichiometric equation Eq. 7.7. An air to fuel ratio, AFR, was chosen as to obtain an excess air ratio, λ, of 1.67 and a combustion gas temperature of 1325 °C.

This was achieved by the mass and energy balances below.

$$CH_4 + 2\lambda(O_2 + 3.76N_2) \longrightarrow CO_2 + 2H_2O + 2\lambda N_2 + 2(\lambda - 1)O_2 \tag{7.7}$$

$$\lambda = \frac{\mathrm{AFR}}{\mathrm{AFR}_{\mathrm{Stoich}}} \tag{7.8}$$

$$\dot{m}_{\mathrm{B2}} = \dot{m}_{\mathrm{B4}}\mathrm{AFR} \tag{7.9}$$

$$\dot{m}_{\mathrm{B3}} h_{\mathrm{B3}} = \dot{m}_{\mathrm{B2}} h_{\mathrm{B2}} + \dot{m}_{\mathrm{B4}} h_{\mathrm{B4}} \tag{7.10}$$

The enthalpy h_{B4} was set to the heating value of methane. The water content of the inlet air was set equal to ambient air while the one of the flue gases was found based on the stoichiometric equation. During the normal operation, no condensing of the flue gases occurred, it was necessary to account for the possibility of water condensation in the combustion air pre-heater for the cases described in the following sections.

The refrigeration unit was based on a simple vapour compression cycle using Ammonia (R717) as a refrigerant. The compressor was modelled analogue to Eq. 7.5 with an isentropic efficiency of 0.75. The evaporator was split into two parts, one for evaporation and one for super-heating. The condenser was split into a cooling, condensing and sub-cooling region. It was assumed that there is 1 K sub-cooling and super-heating respectively. The valve was, in the energy model, considered with a constant enthalpy.

$$h_{\mathrm{RM5}} = h_{\mathrm{RM6}} \tag{7.11}$$

Dairy properties

The composition of the product flow throughout the system is changing, as separation and evaporation processes take place. This impacts the thermal properties, i.e. heat capacity, of the dairy flows. Based on the correlations and milk composition given [274], the heat capacity of the different milk products was found as a function of the composition (fat, protein, carbohydrates, ash and water) and temperature. An overview of the milk compositions used in this production line can be found in Appendix B.1.

7.2.2 Analysis

The analysis of the dairy factory consists at first of a conventional energy mapping and analysis which could be applied in the consultancy using factory data and measurements without any modelling. These types of energy mappings were observed at a project partner. Secondly, the pinch analysis is shown, as a more advanced method for energy efficiency within the industry. Thirdly the methods for exergy and advanced exergy analysis are presented as applied to the dairy plant model.

Energy mapping

The energy mapping, as often used in consultancy, consists of the process analysis and the determination of all relevant components, mass flows and temperatures. This analysis is also the starting point for all other methods, however this mapping usually centres around the components with a high steam or ice water use, i.e. heaters and coolers. The other methods require more detailed analyses, resulting in the process information shown in Section 7.2.1.

The overall aims of the energy mapping are to (i) establish an overview of the energy use in the factory, (ii) find inefficient components and (iii) locate possibilities for energy efficiency improvements, while requiring a minimum amount of data and modelling effort. These aims were achieved by establishing the heating and cooling demands for all components. This was done by using the annual mass flows, which were known to a high accuracy based on the production volumes. Furthermore, the temperature differences, which were obtained from the Piping and Instrumentation Diagrams (P&ID) and, if necessary and available, measurements, were required for the energy balances. Performance indicators, which were obtained from data sheets and other reference factories, were also used for components with none of the above data being sufficient to determine the energy use. Based on this information the temperature difference over the product side for each heater and cooler was calculated and compared to reference values from experience. If the temperature differences appeared higher than what was typically feasible, while also accounting for the energy prices, extensions of the heat transfer area were recommended. By accounting for all thermal energy uses, their distribution by temperature was investigated to find overlaps between heating and cooling demands, which could indicate the possibility for process integration.

Pinch analysis

Process integration techniques are powerful tools that aim at minimising the use of external energy utilities (e.g. heating by a boiler or cooling by a refrigeration cycle) by maximising internal heat recovery and possibly adjusting the process parameters. It was also applied to industrial sites, as discussed in Smith [24] and Klemeš [275], and to dairy factories by Atkins et al. [276].

The pinch method was introduced in Section 2.3 and can be subdivided into four steps: (i) data extraction, similar to or based on the energy mapping; (ii) definition of a minimum temperature difference, which sets the heat transfer potential between two streams in a given heat exchanger; (iii) evaluation of the maximum internal heat recovery and minimum utility demands (setting thermodynamic targets) and (iv) proposing system improvements by means of a re-design of the heat exchanger network (retrofit) or integration of processes such as cogeneration and heat pumping.

Exergy analysis

The concept of exergy, as the maximum work that can be performed by a system when it is brought into equilibrium with its reference environment, was introduced in Section 2.5. In this analysis the physical exergy content of the streams was considered. There were no chemical reactions taking place within the system under study, except the combustion of methane. The changes of chemical exergy due to mixing and separation effects were negligible in comparison with the variations of physical exergy. Changes in chemical exergy were accordingly not considered in the present analysis besides the fuel conversion processes. The specific chemical exergy of the gaseous fuel was approximated based on Moran [277] by Eq. 7.12. The parameters α and β represent the number of carbon and hydrogen atoms in the fuel, respectively. The chemical exergy of the combustion gases was further found using the standard chemical exergy [49].

$$e_{\text{fuel}}^{\text{CH}} = \left(1.033 + 0.01698\frac{\beta}{\alpha} - \frac{0.0169}{\alpha}\right)\text{LHV} \tag{7.12}$$

The exergy product $\dot{E}_{P,k}$ and exergy fuel $\dot{E}_{F,k}$ of the component k were defined based on the component function and are calculated from the inflowing and outflowing exergy streams. The main system components were heat exchangers operating above the environmental state, and the product exergy is commonly defined as the increase of exergy related to the heating of the cold streams [21]. However, several heat exchangers operated across the environmental state, and their exergy products and fuels were thus not trivial. If all streams crossed the environmental state, the product exergy was defined as the sum of the exergy streams at the outlets and the fuel as the sum of exergy at the inlets. If all streams were below the environmental state, the exergy difference of the hot steam was the product and the difference of the cold stream the product. Exergy losses were further considered when a stream crossed the system boundary. Exergy losses, as can also be seen in Figure 7.1, were the exhaust gasses from the hot and cold utility, the dryer and condensate from the evaporators.

The dead state in this analysis was defined as being the ambient pressure (1 bar) and a temperature of 15 °C.

Advanced exergy analysis

The real potential for optimising a given system cannot be assessed by a conventional exergy analysis, as this method disregards the mutual interdependencies of the system components and technological limitations [53, 56]. These drawbacks can be addressed by conducting an advanced exergy analysis, which divides the exergy destruction into its endogenous and exogenous parts, and into its unavoidable and avoidable parts. The concept was introduced in Section 2.5.3 of the present work.

The unavoidable exergy destruction is defined as the remaining exergy destruction when the component of interest is designed for highest thermodynamically possible performance and economically feasible limit. The value for the unavoidable exergy destruction is obtained by Eq. 7.13.

$$\dot{E}_{D,k}^{\mathrm{UN}} = \dot{E}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{\mathrm{UN}} \tag{7.13}$$

Following [55] the modified exergy efficiency ε_k^* was used to describe the avoidable exergy destruction in the kth component.

$$\varepsilon_k^* = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k} - \dot{E}_{D,k}^{\mathrm{UN}}} \tag{7.14}$$

The exogenous part of the exergy destruction $\dot{E}_{D,k}^{\mathrm{EX}}$ within the k-th component is related to the irreversibilities imposed on the component by the other components present in the system. It is found using Eq. 7.15.

$$\dot{E}_{D,k}^{\mathrm{EN}} = \dot{E}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{\mathrm{EN}} \tag{7.15}$$

The real operating conditions shown in Table 7.1 and minimum temperature differences found in Appendix B.2, were the ones found at the factory. These conditions were used here to reveal the real potential of improvement. Existing improvement opportunities of the system components are the avoidable conditions, which can be obtained with technically and economically feasible changes. They are shown in the second column in Table 7.1 and for heat exchangers, based on the fluids, in Table 7.2. The values for the heat exchanger, compressors, ejectors and valves were based on systematic assumptions, taking values reported in the literature into account [58, 263, 278]. The values for AP and AFR in the unavoidable conditions were chosen so that the process can realistically still take place, considering the materials (flame temperature) and air temperature. The theoretical conditions, expressing the thermodynamically ideal conditions are given in the last column of Table 7.1. For heat exchangers the theoretical minimum temperature difference is 0 K. The theoretical value of AFR is equal to the stoichiometric air to fuel ratio for a complete combustion of methane. The theoretical values for the air to product ratio of the SD and FB were chosen, so that the air had sufficient heat to absorb the water, while there was no condensation taking place throughout the system (relatively humidity below 1).

Table 7.1: Real, unavoidable and theoretical operating conditions of components in the production line.

Component			Real	Unavoidable	Theoretical
F1	Compressor	η_{is}	0.75	0.95	1
F2	Ejector	η_N, η_{Di}	0.92	0.95	1
S5	Spray Dryer	AP-Ratio	16.5	15	11.25
S6	Fluidised Bed	AP-Ratio	0.93/ 1.65	0.80/ 1.50	0.67/ 0.55
U1	Burner	AFR	30	20	17.2
R1	Compressor	η_{is}	0.75	0.95	1
R3	Valve	η_{is}	0	0	1

Table 7.2: Unavoidable minimum temperature differences in heat exchangers based on fluids.

$\Delta T_{\text{min}}^{\text{UN}}$ in [K]	Evaporation	Water	Milk	Cream	Concentrate	Air
Condensation	1	1.5	2	2.5	3	4
Water	1.5	2	2.5	3	3.5	5
Milk	2	2,5	3	3.5	4	6
Cream	2.5	3	3.5	4	4.5	7
Concentrate	3	3.5	4	4.5	5	8
Air	4	5	6	7	8	10

The theoretical system is usually simulated with either a constant exergy product or fuel [53]. However, in this case it was not practical as the actual product of the overall system was hardly definable in a thermodynamic sense. For example, the pasteurisation and cooling of streams was required, but the streams were after these operations in the same thermodynamic state. Additionally, there were different sources of fuel, as well as internal heat recovery loops, which could not be kept constant. The simulations were thus performed with a varying fuel and product relating the endogenous exergy destruction to the one of the real system using Eq. 7.15.

7.3 Results

In the following the results obtained with each method are first presented, followed by a summary of the main outcomes and a comparison of the methods. The analysis of the results generally aims at finding inefficiencies or potentials for improving the system and to find the minimum demands, meaning the minimum in externally supplied heat and cooling.

7.3.1 Energy mapping

The energy mapping approach resulted in an overview of the components with heating and cooling demands (Table 7.3) and a visualisation of the heating and cooling requirements at different temperatures (Figure 7.6). The use of thermal energy was identified as shown in Table 7.3 which allows to evaluate (i) the optimal degree of regeneration and (ii) the evaluation of product set-points. As the heaters in the MT section are preceded by a regenerative heat exchanger, the temperature difference of the product (T_{out} -T_{in}) over the heater can give an indication of its performance when the temperature difference is compared to other factories. It is thus possible to evaluate the degree of regeneration. Similar, heaters at modern dairy factories can have temperature differences of 3 K to 5 K for milk streams. Comparing these values to the ones found in Table 7.3, the investigation of increasing the heat transfer area could be justified. The higher temperature differences could also be a result of fouling on the plates and should be checked. The fouling layer is only removed if the proper cleaning chemicals and techniques are used [243].

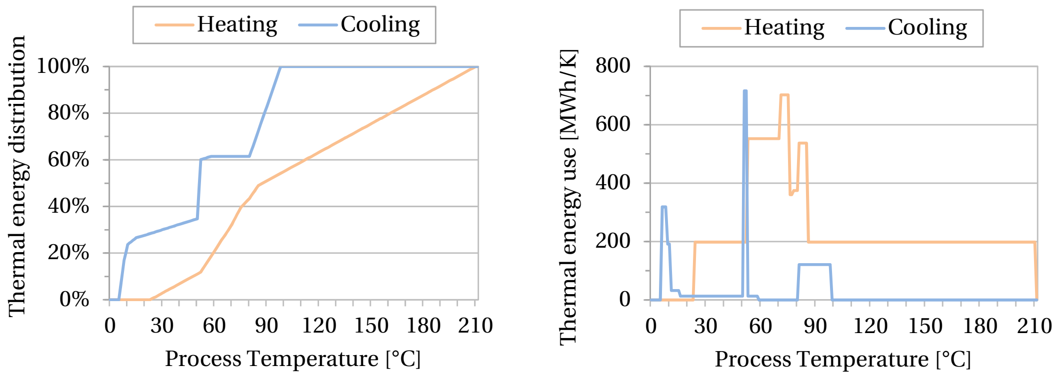
Based on the tables and process flow charts, also some set-points can be questioned. The requirement of cooling the skim milk to 5 °C before adding additives and then heating it again might not be necessary during the whole production. Finding such possibilities based on the information collected during the energy mapping requires some level of previous experience.

Table 7.3: Results of the energy mapping for the identification of potentials for improvement.

	Equipment	Medium	Stream	T_{in} [°C]	T_{out} [°C]	$\dot{m}$ [10^6 kg/yr]	Energy Use [MWh]	
Heating:							Steam	Gas
MT	HEX	Skim Milk	M4	70	75	134.8	749	-
MT	HEX	Cream	C2	77	85	15.1	113	-
MT	HEX	Mixture	M10	80	85	147.4	814	-
EV	HEX	Mixture	E2	75	85	147.4	1,626	-
EV	MVR/ 3TVR	Concentrate	E4	52	75	42.8	7,321	-
SD	HEX	Concentrate	P1	52	75	42.8	829	-
SD	HEX	Air	A4	23	210	709.4	37,033	-
Cooling:							IW	CW
MT	HEX	Skim Milk	M7	8	5	134.8	442	-
MT	HEX	Cream	C5	23	5	15.1	230	-
MT	HEX	Mixture	M12	10	5	147.4	-	794
MT	HEX	Cream	C5	58	23	15.1	466	-
EV	Condenser	Water	VE4	98	80	3.7	2,179	-
EV	Condenser	Water	VE15	52	50	2.5	1,406	-
SD	HEX	Air	A10	15	8	70.6	138	-

In Figure 7.6 the distribution of thermal energy use over the process temperature ranges is shown for heating and cooling demands. From these two figures, it was possible to obtain an indication of, if there were in general possibilities for process integration. There was for instance a cooling demand at around 90 °C which could substitute some of the heating demand (Figure 7.6b). Also between 30 °C and 60 °C, a small cooling demand for the cream was found. The majority of the product cooling however, occurred at temperatures below the ones for the required heat supply and there was in general a considerably higher heating demand.

The large temperature gaps between the utility and heaters on the process sides suggest the use of other heat production methods, such as cogeneration or heat pump units.



(a) Cumulative

(b) Profile

Figure 7.6: Results of the energy mapping for the heating and cooling demands in the processes.

The applied energy mapping approach was to some degree similar to the pinch analysis presented in the next section. The main differences were the number of components and the level of detail (in particular with respect to the evaporators). From the energy mapping it was not possible to find the optimal degree of integration and neither targets including the minimum temperature differences in the system. There was also no strict methodological approach for the analysis, but it was rather based on the individual's experience.

7.3.2 Process integration

Pinch analysis

A pinch analysis of the dairy factory was performed to first calculate the minimum energy requirements of the plant. Figure 7.7 shows the small composite curves for the theoretical streams. The heat load, at which the hot and cold composite curves overlap, can be integrated by means of a heat exchanger network. The largest heating demand then corresponds to the evaporation needs at 75 °C (horizontal part of the cold composite curve), followed by the air heating for the drying of the milk products (cold composite curve above 85 °C). The external cooling demand is negligible, amounting to 0.24 MJ/$kg_{product}$. The pinch point is located at 20 °C, meaning now external cooling is required above and no external heating below this temperature. The minimum heating demand is around 19 MJ/$kg_{product}$ without considering vapour re-compression.

When considering the existing degree of integration at the dairy factory, in particular the vapour re-compression in the evaporators, the grand composite curve (Figure 7.8) can be used to analyse the system. There were no self-sufficient pockets present, meaning that possibilities for internal heat recovery were minimal. The integration of heat pump units through TVR and MVR units is common practice in dairy factories. Water recovered as steam is compressed, either mechanically (MVR) or with high-pressure steam (TVR). The heat that can be recovered from the steam condensation is then used for driving the evaporation process in the same process unit. This allows a close match of the temperature profiles on the hot and cold sides (Figure 7.8). It eliminates the need for external heating within the evaporation section, besides the steam (about 0.3 MJ/kg of product) and electricity (about 0.2 MJ/kg of product) demands for driving the TVRs and MVR. The remaining heating demand, which consists of the heat demand for air heating and concentrate preheating, represents less than 33 % of the original demand.

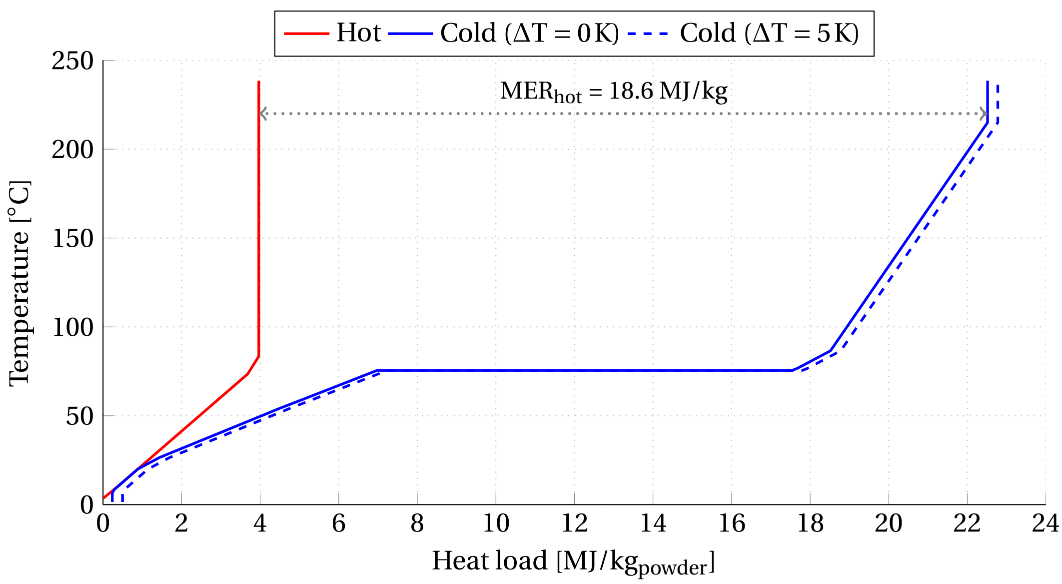


Figure 7.7: Composite curves of the dairy facility, without vapour re-compression and different heat recovery approach temperatures (ΔT).

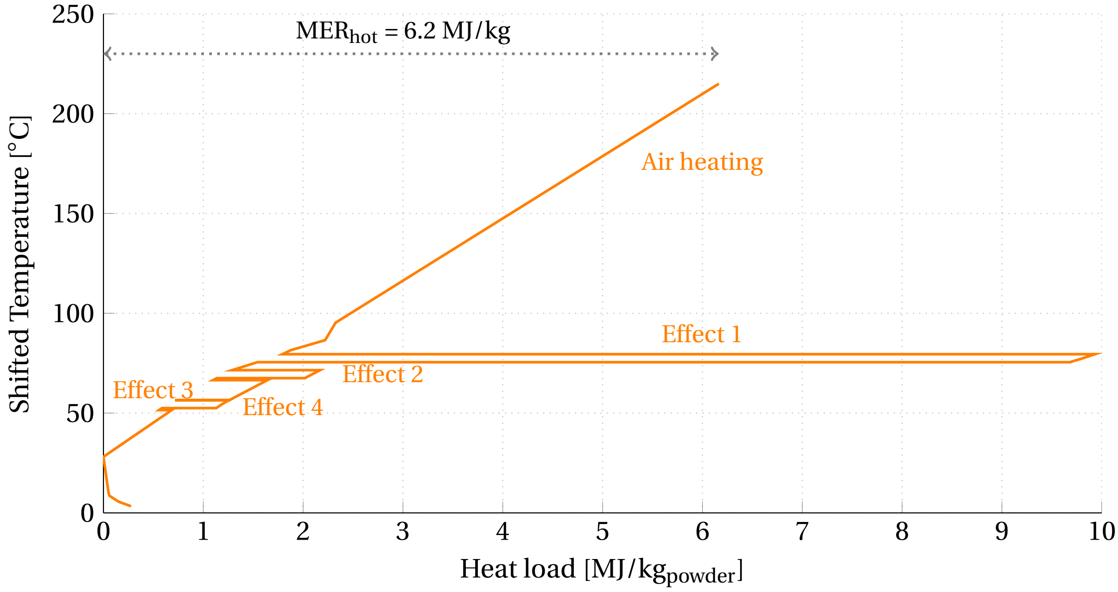


Figure 7.8: Temperature-heat profiles of the dairy facility, with vapour re-compression (TVR and MVR)

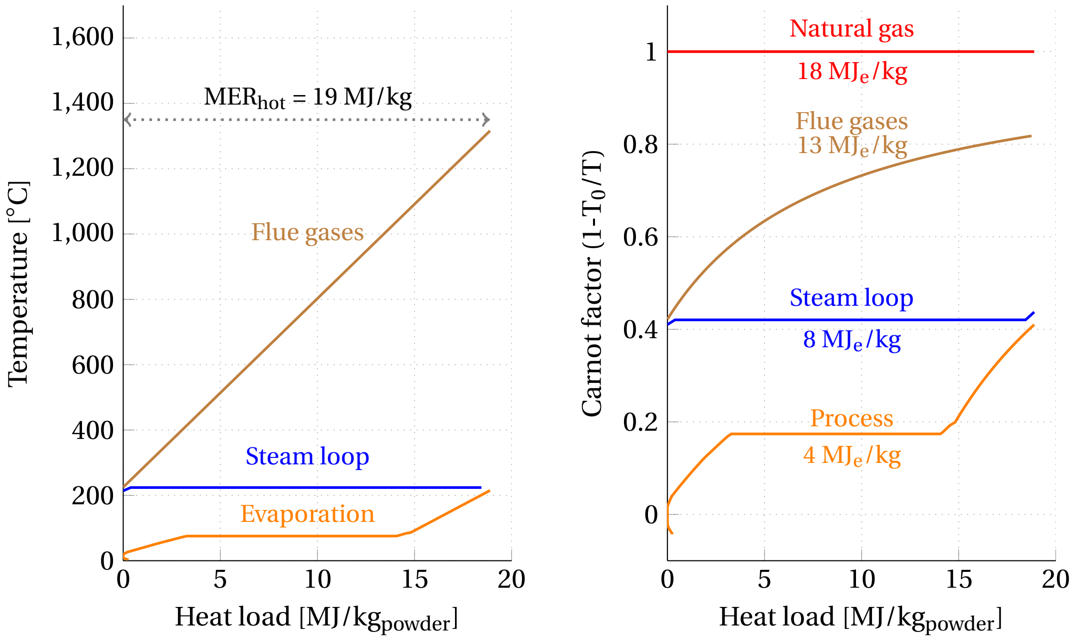
Carnot and utility pinch analysis

The pinch analysis further allows the analysis of the current utility system and its integration with the factory. The heat load is covered with steam produced by natural gas combustion and cascaded from more than 1300 °C to less than 250 °C. The steam loop was designed to cover the highest process temperature in the dairy system as shown in Figure 7.9a.

By plotting the Carnot composite curves [279], the thermodynamic, technological and utility requirement can be analysed. The factory has an exergy demand of only about 4 MJ per kg product. It is satisfied by converting about 18 MJ of natural gas, with about 5 MJ destroyed in the combustion process, and 9 MJ in the heat transfer. The integration of a cogeneration unit would be beneficial from an exergy perspective because of the low to moderate temperature levels for the remaining heating demand. The heat present in the exhaust gases at high temperature can be converted into power, while low-pressure steam can be generated to fulfil the process heat demand. Electrification to satisfy these demands is a promising alternative from an environmental perspective, since there would not be any further need of natural gas, and electric heaters are characterised by a high energy conversion efficiency.

7.3.3 Exergy analysis

The results of the exergy analysis are shown schematically in Figure 7.10 as a Grassmann diagram for the main exergy flows and production sections. In Table 7.4 to 7.7 the detailed results are reported. From Figure 7.10 it can be seen that the highest exergy destruction occurs



(a) Energy basis

(b) Exergy basis

Figure 7.9: Temperature-heat profiles of the dairy factory with the hot utility, without vapour re-compression, on an energy basis (left) and exergy basis (right)

in the hot utility, followed by the SD and EV sections. The exergy loss was small compared to the exergy destruction, but exceeds the exergy content of the dairy products from each section. The main sources of losses are the HU, CU and SD sections. The losses are primarily from exhaust gases from the combustion and drying process, as well as air used in the condenser of the CU. A small exergy loss is present in the condensate from the air preheating in SD facility. Losses in the HU and from the condensate could be reduced by increasing heat transfer in the air pre-heater U3 and S2, while reducing the losses from the drying air and condenser could be achieved by process integration. For the EV section it can also be seen in Table 7.5 that the steam ejector (F2) has three times more exergy destruction than the MVR (F1), while more water is evaporated in the MVR. The replacement of the TVR with an MVR could be beneficial from an exergy perspective as there is less exergy destruction in the compressor, while evaporating more water in this step. The replacement of the steam ejector becomes even more relevant if improvements in the HU are performed as suggested in the previous section.

Considering the exergy destruction ratio for each section, more than 90 % of the exergy destruction occurs in the HU and SD section. Here the steam heating of drying air (S3), as well as the burner (U1) and boiler (U2) have the highest exergy destruction. The combustion of natural gas and heat transfer from the high temperature combustion gases to the steam loop have low exergy efficiency. The regenerative heat exchangers and evaporators typically have a high exergy efficiency, above 80 %. On the contrary, heaters and coolers generally have

Table 7.4: Results of the exergy analysis of the milk treatment (MT) section.

Unit	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	ε_k [%]	$y^*_{D,k}$ [%]
H1	113.0	94.6	18.4	83.7	8.7
H2	125.7	114.7	11.0	91.3	5.2
H3	89.3	35.5	53.8	39.8	25.4
H4	6.9	3.9	3.0	56.6	1.4
H5	17.6	15.4	2.2	87.7	1.0
H6	13.3	6.0	7.4	44.7	3.5
H7	2.5	0.7	1.8	27.8	0.9
H8	338.0	289.0	49.0	85.5	23.1
H9	94.6	43.0	51.6	45.5	24.3
H10	11.2	6.0	5.2	53.5	2.5
H11	11.1	2.3	8.8	21.0	4.1
Total	218.7	55.5	212.1	25.4	1.5

Table 7.5: Results of the exergy analysis of the evaporation (EV) section.

Unit	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	ε_k [%]	$y^*_{D,k}$ [%]
E1	334.7	236.4	98.2	70.7	11.3
E2	195.7	86.1	109.6	44.0	12.6
E3	2695.0	2508.0	187.1	93.1	21.5
E4	142.7	8.0	134.7	5.6	15.5
E5	291.4	240.4	50.9	82.5	5.8
E6	149.2	125.1	24.0	83.9	2.8
E7	126.7	110.4	16.3	87.1	1.9
E8	50.9	2.6	48.3	5.2	5.5
F1	291.1	234.3	56.9	80.5	6.5
F2	369.9	224.6	145.3	60.7	16.7
Total	889.5	-	871.4	-	6.0

low exergy efficiencies. The steam ejector was further found to have a low exergy efficiency, compared to the compressors, while causing more than 16 % of the exergy destruction in the EV section. This further indicates a replacement or reconfiguration opportunity.

Within the CU, a low exergy efficiency is obtained in the condenser (R2) due to the fixed temperature increase of 10 K in the heat sink. This temperature difference could be increased and be made useable, thus reducing the exergy destruction and loss. In this component, 40 % of the exergy destruction from the CU occurs. The burner and boiler in the HU, both have an exergy efficiency of around 60 % while the air preheater (U3) achieves 77 %. The air

Table 7.6: Results of the exergy analysis of the spray drying (SD) section.

Unit	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	ε_k [%]	$y^*_{D,k}$ [%]
S1	95.9	33.0	62.9	34.5	1.5
S2	26.0	6.7	19.3	25.7	0.5
S3	4535.0	2667.0	1869.0	58.8	44.9
S4	2.0	0.5	1.5	25.0	0.0
S5	3036.0	839.9	2196.0	27.7	52.7
S6	23.5	5.4	18.1	22.8	0.4
Total	4635.3	-	4166.8	-	28.9

Table 7.7: Results of the exergy analysis of the hot and cold utility section.

Unit	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	ε_k [%]	$y^*_{D,k}$ [%]
U1	15243	10006	5236	65.7	58.4
U2	9032	5422	3610	60.0	40.3
U3	501	387	114	77.2	1.3
Total HU	16254	6822	8960	42.2	62
R1	306	247	59	80.5	27.6
R2	120	30	90	24.5	42.0
R3	16	0	16	86.9	7.6
R4	101	61	41	60	19.7
Total CU	306	61	208	19.8	1.5

preheater, however, has a negligible share of exergy destruction compared to the other two components. On the other hand, this share becomes relevant on a system level. There are several possibilities to reduce the exergy destruction. Increasing the heat transfer, as well as matching the temperatures in the heaters and coolers, would decrease the exergy destruction in those production components. However, the highly integrated nature of the system, could move some of the exergy destruction to other parts of the factory.

In total the milk powder production facility has an exergy destruction rate of 14.46 MW, exergy losses of almost 0.95 MW and an exergy input of 15.46 MW, an exergy efficiency of less than 1 % is obtained. The product, as shown in Figure 7.10, is however very small. This product only contains the exergy content of the milk stream after each section. Defining an overall product for the system is difficult, as each production step gives a value to the product without being necessarily thermodynamically describable. One main product of the system is however the removal of water from the milk. Despite another part of exergy being used for the thermal treatment, the evaporation accounts for the majority of the exergy use and destruction. If only the evaporated water would be considered as the product, the total system would obtain an

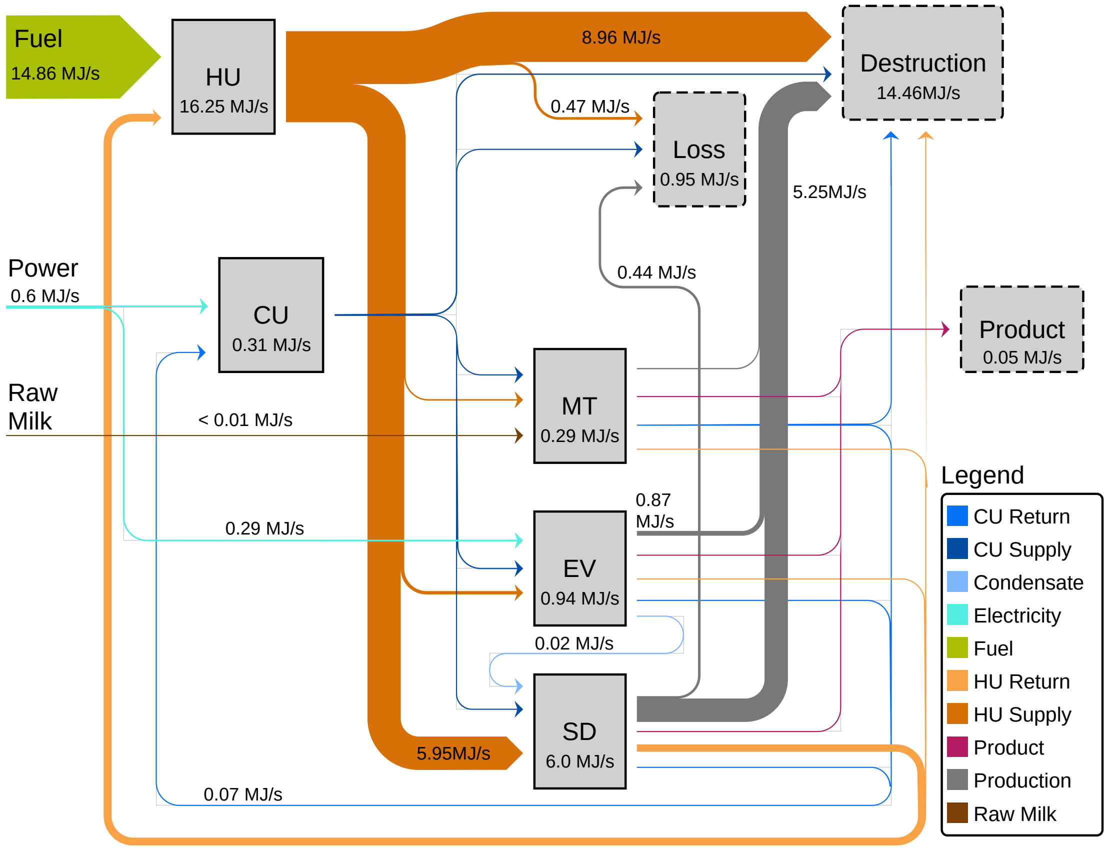


Figure 7.10: Grassmann diagram for the main exergy flows in the system.

exergy efficiency of 35 %. The hot utility supply with steam has an exergy efficiency of 46 % and CU supply with ice water has an exergy efficiency of 22 %.

7.3.4 Advanced exergy analysis

Unavoidable and avoidable exergy destruction The split into unavoidable and avoidable exergy destruction, shows that for the heaters, which had a low exergy efficiency, more than 50 % of the exergy destruction is avoidable (Table 7.8). The evaporators show a similar share of avoidable exergy destruction as shown in Table 7.9. The exergy destruction in the HU (Table 7.11) could be improved by increasing the combustion temperature and decreasing the minimum temperature difference in the boiler and preheater. However, the results show a negative avoidable exergy destruction in all HU components. This is caused by a decreased exergy efficiency through the unavoidable conditions enforced in the other components. For instance, as the condensate (HU1) into the boiler arrives at a lower temperature due to all components operating at unavoidable conditions, the flue gases are cooled down considerably in the boiler (U2). This leads to less preheating at a lower temperature, decreasing the exergy efficiency of the preheater (U3) and of the burner (U1) under unavoidable conditions.

The spray drying section (SD) itself has only a small share of avoidable exergy destruction, which is however large compared to the other sections. The air heater and spray dryer both have high absolute avoidable exergy destruction obtainable from reducing air flows and increasing heat transfer. Considering the dairy sections of the system, considerable amounts of exergy destruction are avoidable. These could be accomplished by primarily increasing the heat transfer of the heat exchangers. The real conditions in the compressors and the current spray dryer would have a lower exergy destruction if more efficient technologies would be implemented.

Endogenous and exogenous exergy destruction The division into endogenous and exogenous exergy destruction shows that the exergy destruction in the heaters H6 and H9 is fully exogenous. This is due to that the regenerative heat exchangers determine the degree of exergy destruction within these components. The regenerative heaters thus have a high share of endogenous exergy destruction, as improvements in the heaters and coolers have no impact on their performance and the inlet conditions at one site are often set-points.

The MVR evaporator (E3) and the first step TVR evaporator (E5), both have a high share of endogenous exergy destruction. Improvements in the other components, i.e. compressor and ejector, only have a small impact on the temperature levels on the condensing site. However, the 2nd and 3rd step of the TVR (E6 and E7) have a higher share of exogenous exergy destruction. The inefficiencies in the preceding steps increase the exergy destruction e.g., due to lower evaporation temperature.

The air preheating with condensate from the evaporators (S2) has a negative exogenous exergy destruction, and in addition the part of endogenous exergy destruction is considerably higher than the real one. Improving the efficiency of the other components reduces the potential for heat transfer in S2. This reduces the total exergy destruction in S2, but also decreases the exergy efficiency, leading to the high endogenous and exogenous values. Similar to this component, the exergy destruction in the HU and in the CU is caused by other components. Optimising the components in the production causes some of the exergy destruction to be shifted to utilities.

It can further be observed, when taking the whole system analysis into account, that improvements on the production site will often have a negative impact on the utility site. This is evident when considering the negative avoidable and exogenous exergy destruction in the utility. So far, improving the heat transfer and matching the temperature of the utility to the production, would increase exergy destruction in the utility. It would thus be necessary to change the current system, to one which benefits from such changes. This could be a heat pump or cogeneration, where lower supply temperatures can increase the overall efficiency.

Table 7.8: Results of the advanced exergy analysis of the milk treatment (MT) section.

Unit	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	ε_k^* [%]	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]
H1	5.7	12.7	88.2	-0.5	18.9
H2	6.5	4.5	96.2	11.0	0.0
H3	46.7	7.1	83.3	53.8	0.0
H4	2.1	0.9	82.0	2.5	0.4
H5	1.0	1.1	93.2	2.2	0.0
H6	6.3	1.1	84.6	0.0	7.4
H7	1.0	0.8	45.3	0.7	1.1
H8	28.4	20.6	93.3	49.0	0.0
H9	45.0	6.5	86.8	0.0	51.6
H10	3.7	1.5	79.6	0.0	5.2
H11	6.9	1.9	55.5	7.2	1.6

Table 7.9: Results of the advanced exergy analysis of the evaporation (EV) section.

Unit	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	ε_k^* [%]	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]
E1	51.6	46.6	83.5	85.6	12.7
E2	95.5	14.1	85.9	105.8	3.8
E3	45.9	141.2	94.7	184.7	2.4
E4	10.3	124.4	6.0	52.9	81.8
E5	37.9	13.0	94.8	49.1	1.9
E6	2.1	21.9	85.1	11.8	12.2
E7	1.9	14.4	88.5	10.4	6.0
E8	4.1	44.2	5.6	13.8	34.5
F1	10.0	46.9	83.4	61.2	-4.3
F2	162.4	-17.1	-	159.0	-13.7

7.3.5 Comparison

At this point a summary and comparison of the main outcomes and suggestions of the methods from the results obtained with the different methods is done. With the energy mapping as presented in section 7.3.1, it can be shown that

- The regenerative heat transfer before the heaters in the MT section could be increased. This result can however only be obtained if engineering experience with similar systems is present.
- The possibility of integrating the cooling demand for cream and in the condensers, with the air heating should be further analysed.

Table 7.10: Results of the advanced exergy analysis of the spray drying (SD) section.

Unit	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	ε_k^* [%]	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]
S1	46.8	16.1	67.2	51.6	11.3
S2	14.4	4.9	57.6	605.9	-586.6
S3	1383.0	486.0	84.6	1849.9	19.1
S4	1.1	0.4	57.2	1.5	0.0
S5	2089.0	107.0	88.7	2196.0	0.0
S6	16.9	1.2	82.1	15.1	3.0

Table 7.11: Results of the advanced exergy analysis of the hot and cold utility section.

Unit	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	ε_k^* [%]	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]
U1	5675	-439	-	7008	-1772
U2	3652	-42	-	3934	-324
U3	1677	-1563	-	7610	-749
R1	10	49	83.4	65	-6
R2	57	33	47.0	79	12
R3	16	0	-	16	0
R4	15	26	-	40	1.6

These results are however highly dependent on the experience of the engineer. For the evaporators, the heating demand was found using the technical documentation, no suggestions for improvement can be made through the mapping. Here it again required experience to judge if the evaporators should be replaced or extended.

Using pinch analysis the following main observations of the system were made:

- The minimum energy requirement for heating of at the factory was determined to be 19 MJ/kg$_{\text{product}}$ and 6.2 MJ/kg$_{\text{product}}$ if vapour re-compression is considered.
- The theoretical heat demand on an exergy basis found using the Carnot composite curves was found to be 4 MJ/kg$_{\text{product}}$
- Internal heat recovery has a small potential, as the processes are also integrated. The utilisation of free steams, e.g. from the exhaust gases of the boiler and dryer could be further investigated.
- Use of co-generation unit to decrease exergy destruction in the utility could be justified by considering the low temperature heating demand.

The exergy analysis has revealed several inefficient components, with respect to exergy destruction and exergy losses. From this the following suggestions were made.

- The exergy flow into the components of the production accumulates to 7.3 MJ/kg in the existing system.
- Prioritise reduction of exergy destruction in hot utility and spray drying section, as they represent a high share of the total exergy destruction
- Evaluation of potential for recovering exergy losses from spray dryer and cold utility, as here the highest exergy losses were found
- Evaluate possibility to replace TVR with an MVR, as the steam ejector has a a high rate of exergy destruction relative to the evaporation effect.

By implementing and performing an advanced exergy analysis, the system was analysed in detail and some of the results from the exergy analysis could be further specified. The overall results are:

- High share of avoidable exergy destruction in heaters and evaporators, where smaller temperature differences should be implemented.
- Improvements in production section will increase exergy destruction in the utility. New utility systems (e.g. heat pumps or co-generation) should be considered.
- Improvements in the spray dryer, e.g. better sealing, insulation and increased product diffusion, should be analysed. Spray dryer has a high absolute value of exergy destruction and a high share of endogenous exergy destruction.

The results of the different analyses are overall coherent. The pinch analysis determined a high optimisation potential by improving the utility system, which is supported by a high share of exergy destruction. The advanced exergy analysis gives some additional insight, when it comes to the component level and the interactions between production and utility. The pinch analysis however, already presents a starting point for the selection and optimal placement for a new utility and for creating an improved heat exchanger network.

The exergy analysis on the other hand showed some potential for heat recovery and reduced exergy loss, which was not directly evident from the pinch analysis and energy mapping. It was further shown that there is a potential for increasing the exergy efficiency of the components. This will not always translate into a reduced energy use. An advantage of the splitting into avoidable and unavoidable exergy destruction is that the possible improvements are directly quantified and become comparable across the system.

As several of the conclusions from all methods could be made by experienced engineers based on the initial process data, the quantification of the potential improvements is an important merit of the methods. The pinch analysis quantifies an overall target for the whole system, while the exergy analysis quantifies the thermodynamic 'inefficiencies', which may not be fully avoidable in practice. The energy mapping does not quantify optimisation potentials, but qualitatively describes improvement options.

The analysis using the energy mapping or the pinch analysis require relatively minor efforts once the all data is collected. Creating the GCC is however not as easy as the diagrams and tables for the energy mapping. Performing the exergy analysis requires more efforts, as each component has to be modelled. The advanced exergy analysis requires in additional several model evaluations, which makes it less practical, and the definition of unavoidable/ theoretical states, which makes it more theoretical.

7.4 Discussion

The studied system is subject to several degrees of uncertainty as some assumptions towards the production and utility had to be done. It was assumed that the operation is constant, however cleaning intervals and batch production can occur. Considering these elements, the pinch analysis could have varying results but the complexity of the problem can increase. Only the production of one product type was considered, as well as only one production line was modelled. In reality the products are different, changing the set-points, and parallel production lines increasing the complexity of interconnected systems. Despite the system being simplified to some degree, the model and results are more detailed than reported in the literature so far.

With respect to the dairy industry, Becker et al. [280] used process integration to find opportunities for heat pump integration in a cheese factory and to improve the methodological approach. By using this process integration, similar to the one in this work using the Carnot scale, considerable cost and CO_2 savings were possible. The method by Quijera and Labidi [247], which combined pinch and exergy to determine the best solar thermal process integration, compares the different solar fractions of the utility in exergy terms. It was found that using only solar energy has a lower exergy efficiency than a natural gas boiler, as the full exergy content of the solar radiation was used. An economic or exergoeconomic analysis is though necessary to find the optimal configuration, as also in this case if a heat pump or cogeneration system was used. Erbay and Koca [249, 281] who performed an exergy and exergoeconomic analysis of a spray dryer for cheese powder production, found that heaters have the highest exergy efficiency of up to 89 %, which is in line with this work. It was further found that the spray dryer itself operates best with a high inlet air temperature and low outlet air temperature. A comparison of the results with the following studies can only be indicative, as not all assumptions and state points are given and different configurations of the systems were used. The results obtained by [251] for the milk spray drying system show that the evaporator is by far the component with the highest rate of exergy destruction. This is contrary to the findings in this work, where the spray drying system has the highest share of exergy destruction. The reason for the difference is that the system used by Yildirim and Genc [251] is single stage evaporator operating solely on fresh steam. The inclusion of multi-effect evaporators with MVR and TVR can thus significantly reduce the exergy destruction of the system. The spray dryers analysed, also have different drying temperatures. The exergy efficiency of the spray dryer in this work is comparable to the one found by Srinivasan et al. [252], who used similar temperatures. The vapour re-compression, presumably using a fan, has a lower exergy efficiency than the MVR and TVR in this work. This is probably due to the much higher outlet temperature of the re-compressed vapour.

7.4.1 Exergy and advanced exergy analysis in industrial practice

Exergy analysis has been previously used as a tool for the analysis of industrial (food) production system [248, 249, 251, 253, 255–257, 265]. As part of this work a complete production system including the utilities was modelled and an advanced exergy analysis of the system was performed. The conduction of an exergy analysis in addition to the normal energy analysis of the system, requires a complete thermodynamic model of the production system. This is often not available from industrial practice, where simpler spreadsheet calculations are used. The inclusion of an exergy analysis requires only minor model additions to the thermodynamic model. However, the implementation of the unavoidable and theoretical conditions, is connected with major challenges. There are many set-points in the production which cannot be modified as they are set to ensure product quality, which consequently results in components which operation cannot be justified from a thermodynamic perspective. This is in particular the case for the pasteurisation units, which have heat the fluid to the given set-point temperature. This requires the finding of workarounds which are sometimes distanced from the actual system. For instance it was not possible to enforce the theoretical conditions in all of the components of H1 to H4, as the unbalanced regenerative heat exchanger would violate the 2nd law of thermodynamics. In the theoretical conditions it was thus necessary to keep a minimum temperature in H3.

Due to the theoretical nature of the split into unavoidable and avoidable, but i.e. into endo- and exogenous conditions, only some of the results are significant for industrial practice. However, it becomes evident that improvements should be targeted to the regenerative heat exchangers and evaporators, where the exergy destruction was found to be both avoidable and endogenous.

As it was shown through the advanced exergy analysis, there are strong interdependencies between improvements in the production and increasing exergy destruction in the utility system. The advanced exergy analysis could be extended to determine the other components contributions to the exogenous exergy destruction in one component. However, the practicability of performing such an analysis will be challenging, as well as the engineering relevance to rigidly defined production steps in the dairy could be questionable. For a complete change of the utility system however, several advantages can be found using exergy analysis, as it clearly shows that a large fraction of the fuel is destroyed and that the exergy destruction may increase with improvements in the production system.

The results show several improvement possibilities. However, it is unclear if those can be implemented in practice. If for instance the unavoidable temperature differences in the heaters and coolers were implemented, the residence time in those components could increase. This would have unwanted effects on the product quality. When advocating measures to the owners and staff of the factory, the reasoning of the suggestion is also important. One possible barrier found for the implementation of cost-efficient energy efficiency measures is the form and credibility of information [282]. It will be challenging to communicate to staff at the production site, the results on a basis of an advanced exergy analysis. Here, other methods can have an advantage.

7.4.2 Comparison of methods

The basis for the application of all methods is to retrieve the required process layout and data. This becomes very time consuming in most cases, as all applied methods require detailed information for each process step and stream. The dairies however measure only certain set-point temperatures, which can vary based on the final product, and have primarily importance for the product quality and not energy use. Finding this information is comparable for each method, however the model for exergy analysis requires more accurate data. Small unbalances in temperatures and flow rates, in e.g. estimates, may have only small impact on a pinch analysis, but have to be eliminated for a complete thermodynamic model. The energy mapping approach has a focus only on the components with actual energy use from the utility and some simplifications with data sheet information are made, which reduces the work load. The impact on uncertainties in the different approaches should be investigated in future works.

Performing the exergy analysis requires only small additional efforts with respect to the model. The definition of the products and fuels is often difficult or not relevant for many components, but requires thorough consideration if useful results are to be obtained. The next level, splitting the exergy destruction into unavoidable and avoidable, was done with reasonable efforts. However, it requires time to implement new conditions, without violating product set-points, in an inflexible system like dairy treatment. The results however are useful to obtain a quantification of the real potential for improvement. In the last step, splitting the exergy destruction into endo- and exogenous, the flexibility of the model has to be increased to allow the theoretical conditions. Furthermore, the number of simulations of the systems is equal to the number of components, increasing the computational time. Though the results are difficult to communicate and some might have no practical relevance, a good understanding of the interactions within the system are obtainable.

The communication of the results to non scientific personal might however be easiest with pinch analysis. The presentation of the results as shown in Figure 7.6 can be easily understood, as the "pockets" within the curve show the direct integration potential. The visualisation in form of composite curves, can be a useful tool too, but the interpretation requires knowledge about the method.

The practical feasibility of the obtained potential for improvement requires further a technical and economic feasibility analysis. Here a heat exchanger network could be established using the pinch analysis as basis or using mathematical programming [32]. A natural continuation of the exergy analysis would be to perform an exergoeconomic analysis [283] or, considering the advanced method, an advanced exergoeconomic analysis [54].

7.5 Conclusion

In this chapter a milk powder production system consisting of a milk treatment, evaporation and spray drying section together with the utility system supplying heat and cooling to the production was analysed. The aim of this chapter was to analyse the system and find optimisation potentials, using different methods. Furthermore, the applied methods, i.e. energy analysis, pinch analysis, exergy and advanced exergy analysis, were compared and the applicability for industrial practice discussed.

The energy analysis, focusing on the main components, was the first step in defining the system. From this basic analysis, first potentials for improving the system were found, which however strongly relied on the availability of previous experience. On the other hand, these findings were expected to be easy to communicate to non-scientific staff. Using the pinch analysis the theoretical MER was found, as well as the utility system was analysed. The production system was already highly integrated and improvements were merely possible. However, the modification of the utility to consist of a cogeneration or heat pumps, seemed to be an optimisation options.

By performing the exergy analysis several components with a high exergy destruction, such as the hot utility and air heater, were identified. Furthermore, the exergy losses from the utility and spray dryer were quantified, with respect to potential to perform work. The advanced exergy analysis allowed to further refine the results. The heaters and coolers were found to have a high share of unavoidable exergy destruction, which was found to be to a large degree endogenous. Despite the split into unavoidable and avoidable exergy destruction appearing relevant to the system analysis in itself, a split into endo- and exogenous exergy destruction was also performed. The latter is however connected with modelling challenges due to set-points.

8 Process and utility optimisation

In this chapter measures to reduce the hot and cold utility consumption of a dairy factory are analysed and evaluated. This includes a process integration analysis and the design of a heat exchanger network. The optimisation of the utility is done with the implementation of a heat pump to supply heating and cooling to the system. At last, the use of solar energy to supply process heating is technically and economically analysed and evaluated with respect to the uncertainties.

8.1 Introduction

In the previous chapter, a more theoretical approach to the methods which can be applied to optimise the dairy system was taken and possible options for improvements were highlighted. This chapter focuses on the analysis of possibilities to implement energy efficiency measures and to replace existing utility systems of industrial energy systems with more sustainable and cost-efficient ones.

To reach this aim three possibilities were evaluated from a technical and economic perspective: more heat integration, use of solar energy and implementation of heat pumps. A simplified model of the milk power production process presented in Chapter 7 was used to evaluate the different possibilities.

8.1.1 Approach

The work with opportunities to minimise the amount of energy use in industrial processes has to be approached with a rigid method. It is important to obtain a complete overview of all the energy demands and supply systems of the factory, before decisions for optimisations are taken. This will avoid wrong prioritization of projects and bad investments.

The first step is an energy mapping, where the energy needs are systematically analysed for all processes with heating and cooling demands, as well as possible excess heat sources and the utility system. With the energy mapping in place it is then possible to assess the state of energy efficiency of the processes and utility, from which concrete suggestions for improvements can be made. The optimisation should be done by the following steps:

- Optimising the energy need by challenging and questioning process parameters and equipment design
- Internal process integration (heat recovery within the process, e.g. heat treatment section)
- Optimising energy distribution systems
- External process integration (heat recovery across the total production site)
- Optimising utility systems
- External heat recovery (utilizing excess heat for residential heating or other industries)

The work in this chapter follows this approach. First, a process integration analysis was performed to investigate possibilities for heat recovery of a spray drying line. The integration of vapour compression heat pumps was also discussed. Afterwards, a model for solar thermal process integration was developed, which was based on annual hourly global direct and diffuse solar radiation, from which the radiation on a defined surface was calculated. Based on hourly process stream data from the dairy factory, the solar thermal process integration for the most suitable streams were found. The last step included an economic optimisation of the problem to determine the optimal size of the collector field and storage tank.

8.1.2 Simplified milk powder case study

The case study used for the full analysis of the milk powder production line (Section 7.2.1) was simplified in order to make it more practical to apply different methods for optimisation and to evaluate the possibilities to integrate new utilities. The simplified production line consisted of milk and cream treatment, high temperature treatment of the skimmed milk, evaporation, spray drying and powder treatment in fluidised beds. The set-point temperatures and mass flow rates were equivalent to the full case study. The vapour re-compression in the evaporators was not considered, as it cannot be retrofitted and should be included in a separate analysis. The mixing section was removed as it is not necessarily part of the production line. Water cooling of cream and the preheating of drying air were excluded, to study new and possibly better opportunities for heat integration. These modifications simplified the system, but also relaxed some site specific constraints. The process flow diagram of the simplified system is shown in Figure 8.1. The hot streams (H) and cold streams (C) are presented in Table 8.1. The evaporation at 67 °C and condensation of the product vapour was not further considered in the stream table. However the free streams, exhaust drying air and condensate were included.

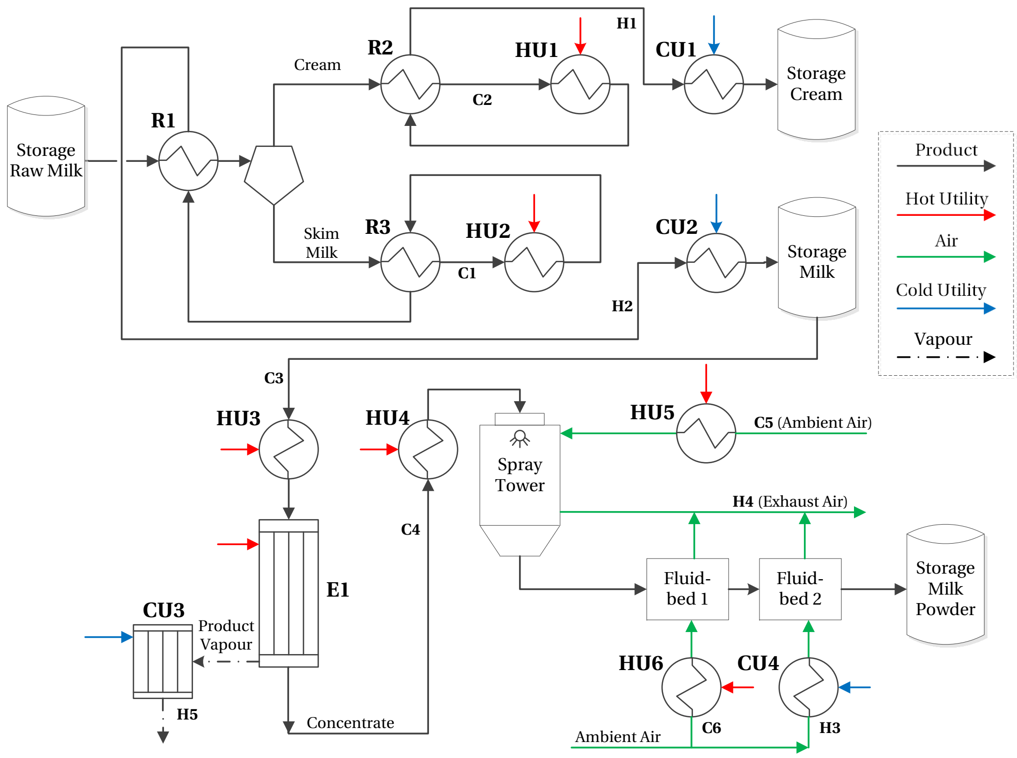


Figure 8.1: Simplified milk powder production line with existing heat recovery.

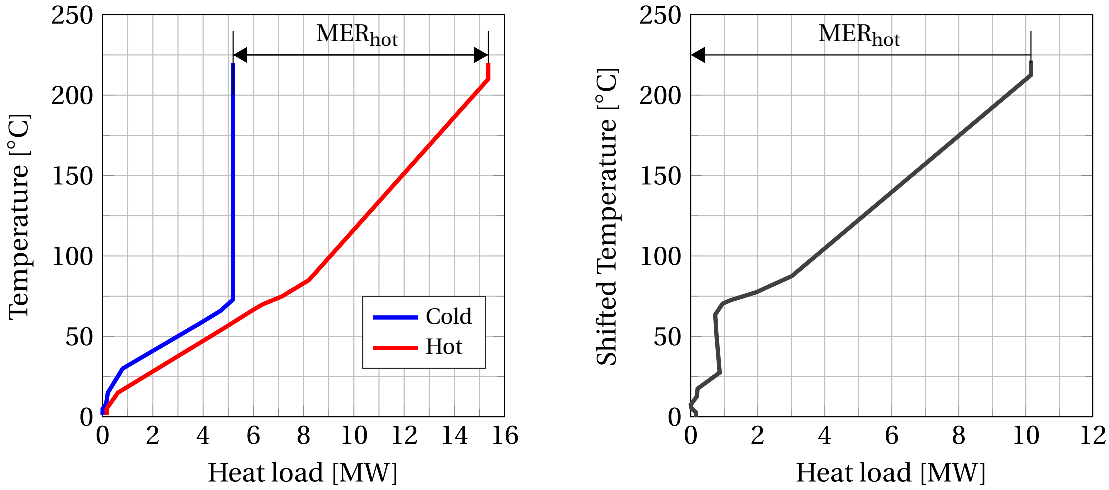
8.2 Process integration

The heat integration was performed following different approaches. The minimum heating and cooling demands, as well as the number of heat exchangers were first found using the problem table algorithm and pinch analysis. Secondly, the sequential approach was used to first find the minimum utility consumption with the LP transshipment model followed by an expansion of the model to find the minimum number and location of heat exchanger units [30]. At the end the heat exchanger network was designed based on simultaneous optimisation using MINLP [32].

A global minimum temperature difference of 5 K was used for all streams. It was further assumed that all streams were connectible and time differences were neglected. The results of the pinch analysis are shown Figure 8.2, not considering the evaporation and including the free streams. The pinch point was located at 7.5 °C. The minimum cooling demand found with the pinch analysis was 0.16 MW and the minimum heating demand was 10.15 MW. This means, that the actual cooling demand of 0.38 MW (excluding free streams) could be reduced by 58 % and the heating demand reduced by 33 %. The minimum cooling demand was by a factor of 2.7 lower than the one from the full dairy case study. The heating demand was however only by around 1 MW lower.

Table 8.1: Stream data considered for the pinch analysis and heat integration study of the simplified dairy factory.

Stream	T_{Supply} [°C]	T_{Target} [°C]	h_{in} [kJ/kg]	h_{out} [kJ/kg]	$\dot{m}$ [kg/s]	$\dot{m}c_p$ [kW/K]	Annual Hours [h/year]
C1	70	75	277.7	297.8	10.7	43.1	5720
C2	77	85	256.3	283.4	1.2	4.1	5720
C3	5	85	19.0	326.8	11.7	45.0	7280
C4	67	75	194.4	217.6	3.4	9.9	7280
C5	15	210	31.3	231.2	55.7	57.1	7280
C6	15	55	31.3	72.0	3.1	3.2	7280
H1	58	5	192.4	16.4	1.2	3.98	5720
H2	8	5	31.7	19.7	10.7	42.80	5720
H3	15	8	31.3	24.2	5.6	5.68	7280
H4	73	30	149.6	104.0	66	70.0	7280
H5	66	15	280.4	62.9	8.3	35.39	7280



(a) CC

(b) GCC

Figure 8.2: Composite curves (a) and a grand composite curve (b) of the simplified milk powder production plant.

The same targets (10.16 MW heating and 0.16 MW cooling) were found using LP. The number of heat exchangers found in the optimal solution was however different than the theoretical minimum number. According to Eq. 2.4 in Chapter 2, the maximum number of heat exchangers was 13 for the given system. The optimal solution found with the expanded LP transshipment model was 14. Also the use of different solvers for the LP optimisation in GAMS [284] did not yield a lower number of heat exchanger units. The transhipment model will usually have more heat exchangers than matches, as it minimises the number of matches [285].

In the third step the optimisation was performed using the simultaneous model for heat integration by Yee and Grossmann [32], as implemented in the GAMS model library. The energy optimal network was enforced by including low costs for heat exchangers and high energy prices, as the optimisation was performed simultaneously for utility costs, heat exchange areas and number of matches. The optimal solution found using the simultaneous optimisation was 13 units, requiring however considerable more computational time than the sequential approach. The heat exchanger network for 13 units can be seen in Figure 8.3. Its integration into the dairy factory is shown in the Appendix C. Also the network consisting of 14 units, found with the transshipment model, is shown in Figure C.1. The optimal network had four regenerative heat exchangers and all cold streams have a hot utility. This could be an advantage in the case of time differences between the hot and cold streams.

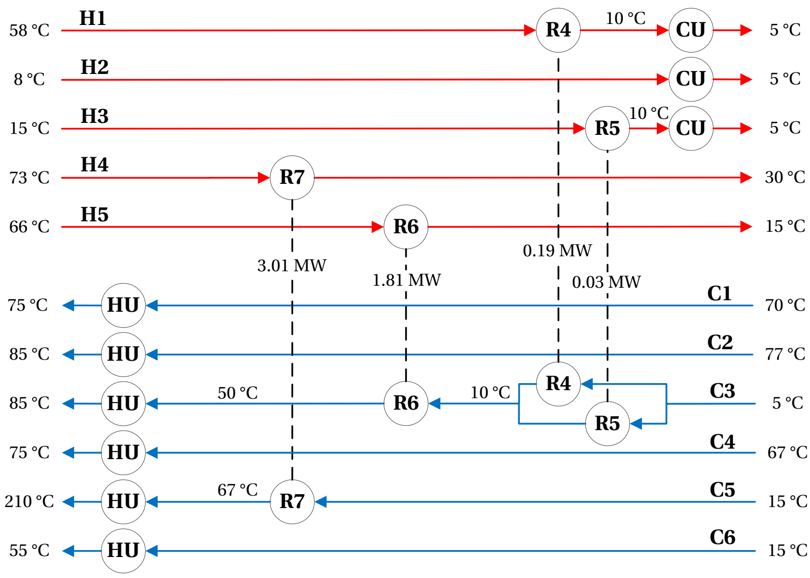


Figure 8.3: Heat exchanger network found with simultaneous optimisation of cost and matches for the simplified dairy factory.

8.2.1 Economic evaluation

For each match an economic evaluation was performed following the approach of approximating the heat transfer area with an estimated overall heat transfer coefficient [195] and the LMTD. This approach was also used in Section 5.2.2 and 6.2.2. The costs for heat exchangers were however found using the cost correlations from Turton et al. [205] for plate heat exchangers, which were used in all calculations within this chapter.

The saved natural gas was found by assuming a combined boiler and steam distribution efficiency of 85 %. A natural gas price for industrial consumers with an annual use of up to 100 TJ, excluding value added taxes and other recoverable taxes and levies, of 37.3 € per MWh was used [286]. All calculations used the HHV of the natural gas. If cooling was replaced, an electricity price of 40.5 € per MWh was used and a cooling COP of 5 was assumed. A technical lifetime of 20 years, a discount rate of 5 %, inflation of 2 % and a natural gas price increase of 5 % were further assumed. The data is summarised in Table 8.3, together with the uncertainty ranges.

The uncertainty was determined using the MC method as described in Chapter 2.7. In the simulations, 18 parameters were varied in the input uncertainty range and 1000 simulations were performed.

Table 8.2: Results of the economic evaluation of the heat exchanger for the new HEN.

		R4	R5	R6	R7
HEX Area	[m^2]	14 ± 2	118 ± 14	261 ± 41	8816 ± 734
Investment Costs	[k€]	56 ± 10	92 ± 22	172 ± 36	2133 ± 581
Savings	[k€ yr^{-1}]	142 ± 34	24 ± 7	1446 ± 354	2331 ± 589
NPV	[k€]	1998 ± 545	303 ± 112	20535 ± 5596	32396 ± 9077
Payback time	[years]	0.4 ± 0.1	3.5 ± 1.1	0.1 ± 0.05	0.9 ± 0.3

Table 8.3: Model parameters base value and their distribution in the input space for the cost calculation of the new heat exchanger network. (Uniform U[lower;upper]; Normal N[μ;σ]; Gamma G[a;b])

	No.	Parameter Name	Value	Unit	Distributions	Description
Energy prices						
Fuel	1	c_{NG}	37.3	€ MWh^{-1}	N[37.3;3.0]	Natural gas price
	2	j_{NG}	5	% p.a.	U[2;7]	Annual fuel price increase
Electricity	3	c_{el}	40.5	€ MWh^{-1}	N[40.5;3.5]	Electricity price
	4	j_{el}	2	% p.a.	U[1;3]	Annual electricity price increase
Economic data						
	5	d	5	% p.a.	U[4;6]	Discount rate
	6	i_{infl}	2	% p.a.	U[1;3]	Inflation
	7	n_{lifetime}	20	years	G[2;2]	Lifetime of new system
	8	c_{subsidy}	50	€ MWh^{-1}	U[40;60]	Lifetime of new system
	9.1	$h_{\mathrm{operating,1}}$	5720	$\mathrm{h\,year}^{-1}$	-	Annual operating hours sub-system 1
	9.2	$h_{\mathrm{operating,2}}$	7280	$\mathrm{h\,year}^{-1}$	-	Annual operating hours sub-system 2
Heat exchanger						
	10	$k_{\mathrm{Milk/\,Milk}}$	750	$\mathrm{W\,m}^{-2}\,\mathrm{K}^{-1}$	U[550;950]	Overall heat transfer coefficient
	11	$k_{\mathrm{Air/\,Air}}$	35	$\mathrm{W\,m}^{-2}\,\mathrm{K}^{-1}$	U[30;40]	Overall heat transfer coefficient
	12	$k_{\mathrm{Milk/\,Air}}$	50	$\mathrm{W\,m}^{-2}\,\mathrm{K}^{-1}$	U[40;60]	Overall heat transfer coefficient
Costs	13	$f_{\mathrm{bare\ module}}$	4.451	-	U[4;5]	Bare module costs
	14	z_1	3.853	-	-	Heat exchanger cost constant 1
	15	z_2	-0.15	-	-	Heat exchanger cost constant 2
	16	z_3	0.15	-	-	Heat exchanger cost constant 3
Heat exchanger						
	17	η_{boiler}	0.85	-	U[0.8;0.9]	Boiler and steam distribution efficiency
	18	$\mathrm{COP}_{\mathrm{IW}}$	5	-	U[4;6]	COP of cooling system

8.3 Integration of heat pumps

In order to reduce the external demand for heating and cooling further, heat pumps can be utilised to supply process heat using either hot streams or other excess heat sources which do not have temperatures allowing a direct heat transfer. For spray drying, often a direct heat transfer is possible as shown in this work and by Atkins et al. [276]. The integration of a heat pump in a cheese factory was performed by [280], where different process integration cases were analysed and compared. A review of cases, methods and the development of methodology for the integration of industrial heat pumps can be further found in [287]. For the production of candies, a heat pump integration was performed by Olsen et al. [288], who also used pinch analysis to find the optimal placement. One important criteria for placing the heat pump was that the heat pump should be placed across the pinch. Thus it was guaranteed that no additional heating or cooling requirements were created.

This section describes the possibility of integrating a heat pump in the dairy system. Three cooling demands remained after the heat integration, which could be theoretically covered by a heat pump, while at the same time supplying process heat. The work in this section is partly based on [289]([C7]) and used the heat pump model described in [200]. The aim was to have a basic evaluation of the remaining opportunities to further reduce the energy use and to assess its economic feasibility.

The approach was to find for each remaining hot stream a corresponding cold stream, which had a heat requirement similar to the cooling requirement of the hot stream. This resulted in three matches (HP1, HP2 and HP3), which are presented in Table 8.4.

Table 8.4: Streams considered for heat pump integration for a combined process cooling and heating effect.

	Stream [-]	T_{Supply} [°C]	T_{Target} [°C]	$\dot{m}c_p$ [kW K]	$\dot{Q}_{demand}$ [kW]
HP1	H2	8	5	42.8	128.4
	C6	*15*	*55*	3.2	126.2
HP2	H1	10	5	3.9	19.7
	C2	77	85	4.1	32.6
HP3	H3	10	5	5.8	29.2
	C4	67	75	9.9	78.9

Using the heat pump optimisation tool, as shown by Zühlsdorf et al. [200], the COP and investment costs for each of the three configurations were found. The sizing of the system was done in order to fully cover the heating or cooling demand, without creating any excess of heat or cooling requirement below or above the pinch respectively. For the heat pump the following parameters were chosen: ammonia as refrigerant, a minimum pinch temperature of 3 K in the evaporator and condenser and an isentropic compressor efficiency of 0.7. The cost correlations were taken as shown in Zühlsdorf et al. [200], with the exception of heat exchanger costs, for which the same correlations as in the previous section were used. The economic feasibility study of each match was done analogue to the heat exchanger network with the same parameters presented in Table 8.3.

Table 8.5: Technical and economic results for the three heat pump configurations in the milk powder factory.

		HP1	HP2	HP3
COP	[-]	5.0	2.7	3.0
$\dot{Q}_{cold}$	[kW]	100.7	20.5	29.2
$\dot{Q}_{hot}$	[kW]	126.2	32.6	43.7
Investment	[k€]	165 ± 31	114 ± 21	121 ± 22
NPV	[k€]	931 ± 304	114 ± 66	288 ± 120
Payback time	[years]	2.3 ± 0.7	7.6 ± 2.3	4.4 ± 1.3

The results for the three configurations are presented in Table 8.5. The highest COP was obtained for the HP1 configuration, as the temperatures of sink and source were closer together. This solution also had the highest NPV and lowest payback time. The second best solution, HP3, had a payback time below 4.4 years. Despite only a slightly better COP than HP2, HP3 had more full load hours due to all streams being located in the spray drying section. Apart from HP2, all other cases were not self-sustained and required additional cooling (HP1) or heating (HP3). Furthermore, only HP2 had a cooling demand always at the same time as the heating demand. The two other cases might require a thermal storage for load balancing.

The investment costs for the heat pumps appear to be considerably overestimated. Wolf et al. [203] found specific heat pump costs of 250 € per kW heating for heat pumps comparable to HP1 and around 500 € per kW heating for heat pumps comparable to HP2 and HP3. The costs found here are by a factor of 5 to 7 higher. Also compared to the cost functions determined in Section 5.2.2, the investment costs are overestimated. The main reason for the overestimation are the small heat transfer areas (below 20 m^2). These areas are in the lower or just outside the allowed range for the cost correlations. The cost for connecting the heat pump (cold and hot side), will require new piping and connections and more expensive materials, due to the equipment being used in food processing, which was not quantified.

It is difficult to visualise the placement of the heat pumps in the GCC, due to the small cooling demand compared to the heating demand. Figure 8.4 shows, therefore, only the integration of HP1. This heat pump already covers most of the remaining cooling demand

The performed analysis showed that opportunities for heat pump integration were available in the dairy case study. The remaining cooling demand could be almost fully covered by heat pumps, if also process heat was supplied at the same time.

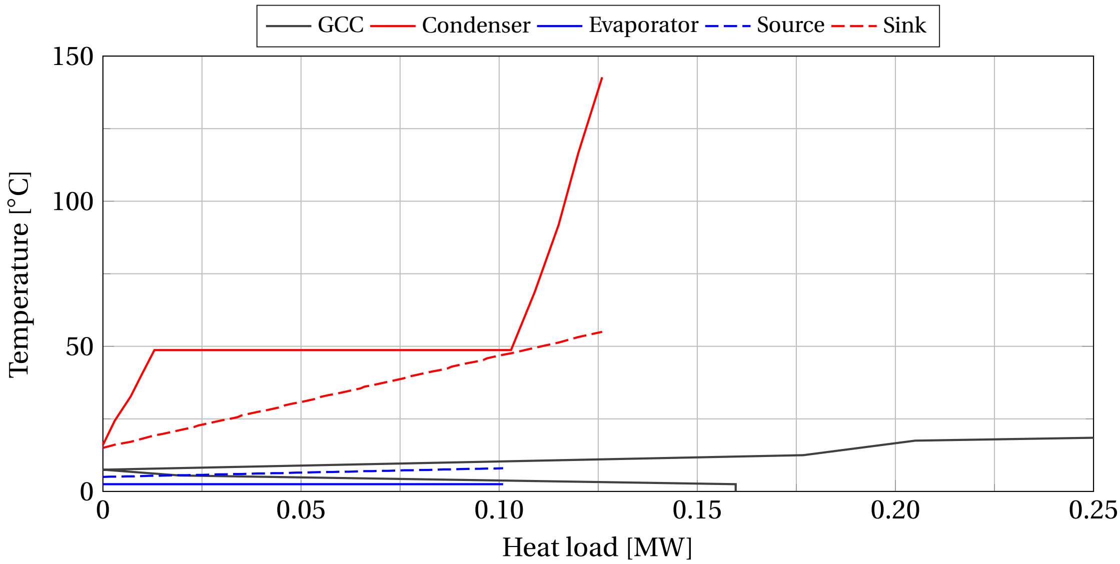


Figure 8.4: Heat pump (HP1) integrated in the system with the GCC.

8.4 Integration of solar thermal systems

The milk powder factory has a high process heating demand at relatively low temperatures (below 100 °C) as it was shown in the pinch analysis in Figure 8.2. The use of solar thermal energy could be used for process heating, if the process characteristics allow a technically and economically feasible integration. It is thus required to determine possible integration options for a solar thermal system and to optimise the size of the components, based on economic considerations.

In this section a solar thermal process integration model is presented, which was based on hourly global and diffuse solar irradiation data. Together with the collector data, the solar irradiation was used to determine the available solar energy. Combining the solar with the process data, the hourly energy balances and control strategy, considering tanks and utility heating, were created. An economic optimisation was further performed to find the optimal configuration between collector area, thermal storage tank size and supply temperature of the solar collector. The optimal solar system was found for each of the remaining cold streams of the dairy factory. The model and results are partly based on [290] ([C6]).

Several of the key input parameters used in the model, had uncertainties which impacted the model output to an unknown extent. It was thus necessary to conduct an uncertainty analysis and to find the most important model parameters using a sensitivity analysis. This detailed analysis was performed for the most economically suited cold stream.

8.4.1 Literature review of uncertainties and industry applications of solar thermal energy

The use of solar thermal systems for district heating has increased within 10 years from 53 TJ to 835 TJ in 2015 [8]. The use of solar energy for industrial process applications is however not common yet [88]. Several studies have been published, analysing the potential and implementation of solar systems into the industry. Schnitzer et al. [291] showed the opportunities of integrating solar thermal energy into processes in Austria. Several processes and industries were presented, which were suitable for a solar thermal energy supply. An Austrian cheese plant was used for an economic analysis. The analysis showed that the solar thermal installation would have a payback time of less than 3 years.

Nemet et al. [292] introduced two curves to the pinch analysis method for solar thermal process integration. The captured solar energy curve (CSEC) shows the maximum obtainable solar energy as a function of the capture temperature and the minimal capture temperature curve (MCTC) representing the minimum temperature at which the hot process demand can be covered by the solar systems from the thermal storage, while ensuring feasible thermodynamics of the heat transfer. At the point where the two curves intersect, the target temperature can be found at which the highest solar thermal coverage can be obtained. The developed method was further applied to a single process and total site example. Nemet et al. [293] further proposed a framework for the process integration of solar thermal into a system with varying demand. The method was based on a time slice model, for which the user can set the accuracy based on a varying solar energy availability over time. Furthermore, a case study was presented consisting of four streams for which the heating requirements were satisfied by heat recovery, solar thermal, stored solar thermal energy and an external utility.

The solar thermal process integration, in the case of a milk powder factory, was performed by Atkins et al. [294], where the authors focused on the solar collector performance based on solar radiation, the collector fluid temperatures and mass flow rates. Walmsley et al. [295] further investigated the integration of a heat recovery loop and solar energy for sites with a low pinch temperature. More recently, Walmsley et al. [296] compared three options for the integration of solar thermal into the heat recovery loop of a milk powder plant. The systems were dynamically modelled and show that the optimal placement for the solar collectors was in series with other heat sources.

Quijera et al. [250, 297] analysed the integration of solar thermal collectors and reuse of warm waste water in a dairy plant for a specific case in the Basque country. The work focused on the modelling of the solar system and different combinations of process integration and solar thermal use. This case study was extended by Quijera and Labidi [247] by including exergy as an indicator to compare different scenarios.

Lauterbach [298] analysed the potential of solar thermal energy for the industry in Germany. Schmitt [299] focused on the temperature ranges required at the industry and which of them could be covered by solar thermal installations.

With respect to uncertainty analysis of solar thermal systems in numerical models, several works were published. Dominguez-Muñoz et al. [300] proposed reliability analysis methods to strengthen the engineering practices when designing solar thermal hot water systems. To perform the uncertainty analysis, the Monte Carlo method and samples created with the LHS technique were used. The sensitivity analysis was performed with Monte Carlo Filtering. The results show the influential factors in the design are the boiler set-points, solar radiation, the demand and demand profile. Economic factors, which would show the trade off between probability of failure and costs, were not taken into account.

Meybodi and Beath [301] performed an analysis of cost uncertainties and solar data variations on the economics of central receiver power plants in Australia. They used Monte Carlo simulations for the plant specifications. For each specification the authors chose a most likely, maximum and minimum value, which were used in a triangular distribution to produce randomised data. The authors concluded that the thermal storage size has minimal impact on the levelized costs of energy, as opposed to the solar resource quality.

Mathioulakis et al. [302] focused in their work on the uncertainty in the performance of solar thermal systems. The uncertainty characteristics were found first for experimental measurements of the system, secondly for the imperfections of the energy model and lastly for the actual operation of the solar system. Also here, Monte Carlo techniques were used. The study showed that Monte-Carlo simulation techniques were an effective solution for the estimation of uncertainties. The contribution of the uncertainties with regards to the measuring devices were low, but were high for the energy model. The uncertainty of the energy model were considerable due the use of data for a typical meteorological year. The total uncertainty of the energy output of the solar system was found to be 9 %.

8.4.2 Methods

In this section the overall approach for the process integration of solar thermal energy is explained. It was performed for the system shown in Figure C.2, which shows the simplified dairy plant after heat integration. The model structure and its elements are shown in Figure 8.5.

The approach for the solar integration consisted of the following steps for the already heat integrated industrial site:

1. Definition of constraints and system of the solar thermal plant in particular: available area, tilt angle, orientation and technology
2. Computation of available solar energy based on hourly global irradiation
3. Definition of temperature set-points and control strategy
4. Economic optimisation of solar collector area and thermal storage tank size
5. Uncertainty analysis of the optimal solution
6. Sensitivity analysis of the optimal solution

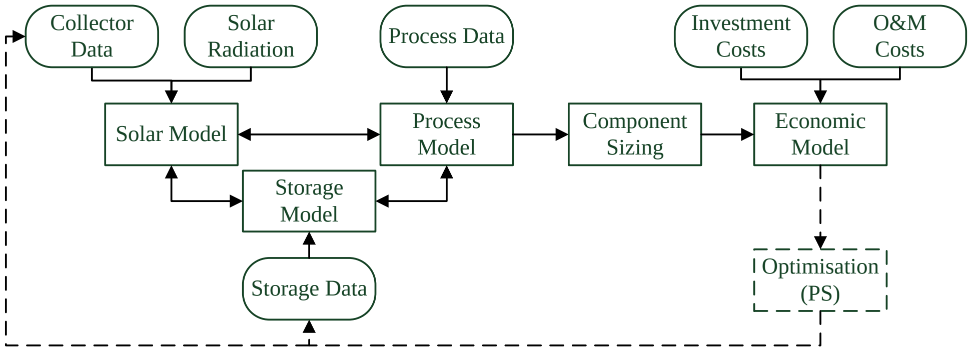


Figure 8.5: Flow chart and main elements of the solar process integration model used in this work. The dotted line shows the optimisation routine which is not part of this work.

7. Evaluate robustness of the results and assess opportunities for model improvement

The model outputs most interesting for the system designer, which were taken into consideration in the proceeding analysis, are the:

- *Annual system costs, C_{system}*: Taking into account the annual O&M costs and the repayment of the investment costs over the system's lifetime
- *Specific costs of solar energy, c_{solar}*: Taking into account the cash flows associated to the solar system over the lifetime, divided by the thermal energy delivered
- *Payback Time*: Investment costs divided by the annual system costs
- *Solar fraction, SF*: The fraction the energy input covered by the produced solar energy directly, without being stored in the thermal storage.
- *Solar energy supplied, Q_{solar}*: The amount of solar energy supplied corresponds to the fuel saved compared to a system without solar energy.

System Modelling

The modelling of the solar system consisted of two parts. The first part determined the solar irradiation available, using the geographical location as well as the orientation and tilt angle of the solar collectors. Secondly, the conversion efficiency of the solar irradiation reaching the collector to the thermal energy available for process heating was established.

Solar Irradiation The energy supplied by the solar thermal system depends, besides the characteristics of the collectors, on the solar radiation reaching the collector area A_{solar}. The developed model used hourly horizontal direct and diffuse irradiation data. Shading losses from external objects were neglected. The solar energy reaching the collector consists of

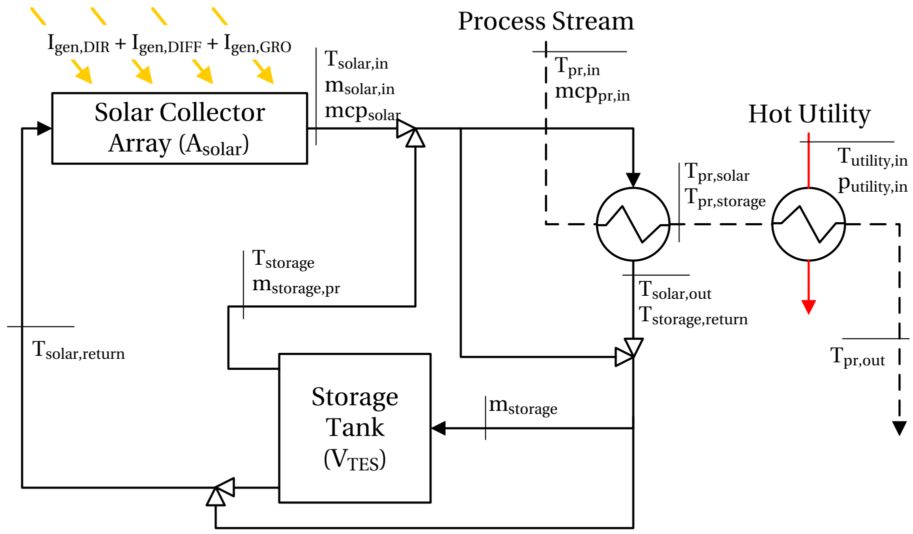


Figure 8.6: Flow chart and main elements of the solar process integration model used in this work. The dotted line shows the optimisation routine which is not part of this work.

the direct ($I_{\text{gen,DIR}}$), diffuse ($I_{\text{gen,DIFF}}$) and ground-reflected ($I_{\text{gen,GRO}}$) radiation. The direct radiation on a surface with the tilt angle ζ_{gen} and the azimuth angle α_{Solar} was calculated based on Duffie and Beckman [303] with equation 8.1.

$$I_{\text{gen,DIR}} = I_{\text{hor,DIR}} \frac{\cos\theta_{\text{gen}}}{\sin\zeta_{\text{Solar}}} \tag{8.1}$$

In this equation the solar incidence angle θ_{gen} was calculated as a function of the collector orientation and the sun position [304]. The sun elevation ζ_{Solar} and solar azimuth angle α_{Solar} were obtained based on the calculation procedure by [305].

The diffuse radiation was calculated with the diffuse irradiation model by Perez et al. [306]. The corresponding model coefficients for the circumsolar and horizontal brightening coefficient were taken from Perez et al. [307]. The ground reflected radiation reaching the solar collector was calculated as a function of the Albedo factor using the conversion model of Perez and Stewart [308].

Solar Collectors To obtain the efficiency $\eta_{collector}$ at which the solar irradiation I_{gen} was converted into thermal energy of the collector fluid the correlation Eq. 8.2 was used [250, 303]. The equation includes the calculation of an incidence angle modifier k_θ, which is based on the sun position for every time step and the collector type.

$$\eta_{\text{collector}} = \eta_0 k_\theta - \frac{a_1 \left(T_{\text{collector}} - T_{\text{ambient}}\right) + a_2 \left(T_{\text{collector}} - T_{\text{ambient}}\right)^2}{I_{\text{gen,DIR}} + I_{\text{gen,DIFF}} + I_{\text{gen,GRO}}} \tag{8.2}$$

Furthermore, the ambient temperature T_{ambient} and mean collector temperature $T_{\text{collector}}$ were used, together with the heat loss factors of the solar collector a_1 and a_2, as well as the optical efficiency η_0. The temperature $T_{\text{collector}}$ was the average between outlet and inlet temperature of the collector fluid to the collector, for which an outlet temperature of 85 °C was chosen. The inlet temperature was defined by the process stream inlet temperature and the minimum temperature difference of the solar to process heat exchanger.

Thermal Storage Tank The storage tank was modelled as a fully mixed tank, meaning that the liquid in the tank had a uniform temperature. For each time step the tank temperature was recalculated, based on the inflow and the outflow to process heating or return to the collector.

Heat Exchanger Two heat exchangers were used for heating the process stream. The first one was heating the process stream with fluid from the solar collectors or the storage tank, the second one with steam from the utility. The first heat exchanger was designed for the most frequent operation condition and the second one for operation without solar energy, for both using the LMTD method [309]. Based on the design value, their operation in off-design was modelled using Eq. 8.3. The heat transfer coefficient, h, on the inside or outside of the tubes (in a shell and tube heat exchanger) was found based on the design values and the exponent γ (0.8 inside and 0.6 outside of the tube) [310].

$$h = h_{\text{design}} \left(\frac{\dot{m}}{\dot{m}_{\text{design}}} \right)^{\gamma} \tag{8.3}$$

Economic Analysis

The investment and the operating costs of the system were considered for the economic optimisation. The investment costs for the equipment were estimated based on correlations shown by Bejan et al. [21] and Turton et al. [205]. Fuel prices were based on the Danish market and all costs were corrected for the year 2014. The time value of money was considered by including inflation, the future increases in fuel price and the interest rates for the investment. An investment horizon of 20 years was used. The costs were estimated as explained in Chapter 8.2.1 and the assumed values are shown in Table 8.3 and Table 8.6. The evaluation took place as shown in Section 5.2.2. In addition the specific solar costs, c_{solar}, were found as the sum of the cash flows, corrected for inflation, during the lifetime divided by the solar thermal energy supplied.

Economic optimisation

The optimisation was performed as a nonlinear problem using the *particle swarm* and *pattern search* algorithms in Matlab Optmisation Toolbox [311]. The active collector area (A_{solar}), the thermal energy storage tank size (V_{TES}) and the solar collector outlet temperature ($T_{\text{solar,in}}$) were decision variables. All three of these parameters could be chosen freely. The collector outlet temperature was chosen to be fixed throughout the year. Solar district heating plants often adjust the temperature each month. The Marstal district heating plant in Denmark, for example, adjusts its temperature between 78 °C and 92 °C [312]. The maximum value for the solar outlet temperature was chosen to be 85 °C on an annual basis. The optimisation was further constrained by the land area available for the collector installation which corresponded to 2000 m^2 of active collector area and a thermal storage tank size of 500 m^3. The objective function was the minimisation of the annual operating costs.

$$C_{system} = C_{\text{Natural gas}} + C_{\text{OM,solar}} + \left(CRF\,(I_{\text{solar}} + I_{\text{TES}} + I_{\text{HEX}}) - C_{\text{subsidy}}\right) \cdot n_{\text{lifetime}}^{-1} \tag{8.4}$$

Uncertainty and Sensitivity Analysis

The uncertainty and sensitivity analysis was performed following the approach and methods described in Section 2.7. The uncertainty analysis was done following Monte Carlo (MC) method [71], which was also used for the sensitivity analysis with linear regression. Morris Screening was additionally used.

8.4.3 Model Assumptions

The model contained in total 52 input parameters of which 20 described the solar energy, 7 the industrial process and 25 were economic parameters. Out of these input parameters, 19 had been selected to be included in the uncertainty and sensitivity analysis. The remaining values had either no uncertainty as they were known to a high degree, e.g. latitude and longitude of the plant, or they were design variables, e.g. collector slope and azimuth angle. An overview and summary of the data and input uncertainty can be found in Table 8.6. The distributions were estimated based on literature values [300] and intervals given in the literature where the base values were taken from [21, 188, 205].

It was further assumed that there were no heat losses from components and pressure losses were not considered. The electricity costs for pumping were included in the O& M costs of the solar system [188], but piping costs between the solar collector field and the process were not.

Table 8.6: Model parameter base values and their distribution in the input space for the solar thermal process integration model. (Uniform U[lower;upper]; Normal N[μ;σ]; Gamma G[a;b])

	No.	Parameter	Value	Unit	Distributions	Description
Solar Radiation						
	19	Albedo	0.2	-	U[0.15;0.55]	Standard Albedo Factor (Ground reflectivity)
	20	k_θ	0.08	-	N[0.08;0.008]	Incidence Angle Modifier Coefficient
Solar Collector						
	21	η_o	0.8	-	N[0.8;0.0494]	Optical solar collector efficiency
	22	a_1	1.57	$\mathrm{W\,m^{-2}}K^{-1}$	N[1.57;0.075]	Heat loss coefficient
	23	a_2	0.0003	$\mathrm{W\,m^{-2}}K^{-1}$	N[0.0003;1.5E-06]	Heat loss coefficient
Process Data						
	24	$\dot{m}\mathrm{cp}_{\mathrm{pr,in}}$	45/57	$\mathrm{kW\,K^{-1}}$	-	Heat capacity flow rate of the process stream
	25	$T_{\mathrm{pr,in}}$	50/67	°C	-	Process stream temperature into heater
Investment						
Storage	26	c_{storage}	1000	$€\,\mathrm{m^{-3}}$	U[800;1200]	Reference Costs for storage of $10\,\mathrm{m^{-3}}$
	27	$\gamma_{\mathrm{storage}}$	0.65	-	U[0.55;0.75]	Scaling Exponent for storage
Solar	28	c_{solar}	386	$€\,\mathrm{m^{-2}}$	U[326;446]	Reference Costs for solar field
	29	γ_{solar}	0.75	-	U[0.65;0.85]	Scaling Exponent for Solar Field
O&M	30	$c_{\mathrm{OM,solar}}$	0.57	$€\,\mathrm{MWh^{-1}}$	U[0.5;2]	O&M Solar System

8.4.4 Results

In the following, first the results of the optimisation of each stream are shown, followed by the presentation of hourly results for one day. At the end a more detailed analysis of the optimal configuration is shown.

Economic optimisation

The results of the economic optimisation for each hot utility, remaining after the heat integration in Section 8.2, are shown in Table 8.7. The highest NPV and lowest payback time was obtained for HU3. The optimal solution had the upper bound of A_{solar} with a solar supply temperature of 75.7 °C. The second highest NPV was found for HU5 (air heating). The optimal solution for HU2 was without solar energy, as the heating demand was very low and thus investment costs would be over-proportionally high. HU1 and HU6 had a negative NPV and a simple payback time of more than 14 years. Over the 20 year lifetime, the annualised savings C_{savings} would be more than 30 thousand Euro.

Comparing the two best cases, HU3 was found to be clearly the better option. In both cases, a high number of annual operating hours (7320 hours per year) were assumed, but HU3 had a lower process inlet temperature and had a liquid as process medium. This was also the reason for the lower value of T_{solar} in HU3, as a lower temperature increased the collector efficiency. In HU5 a higher temperature was chosen in order to reduce the cost of the heat exchanger (through a higher LMTD), as the overall heat transfer coefficient was very low for air/water.

Table 8.7: Optimal configuration of a solar thermal system for each hot utility after heat integration.

	A_{solar} [m^2]	V_{TES} [m^3]	T_{solar} [°C]	C_{system} [k€ yr^{-1}]	C_{savings} [k€ yr^{-1}]	c_{solar} [€ MWh^{-1}]	NPV [k€]	PbT [years]
HU1	1162	229.22	85.0	110	48	73.0	-58	14.7
HU2	-	356.25	85.0	19	-	-	-	0.0
HU3	2000	129.08	75.7	1,074	118	38.9	668	7.8
HU5	2000	33.19	85.0	5,902	105	64.1	61	12.9
HU6	748	34.55	84.0	83	35	70.8	-27	14.2

Solar model

In the following an example of the model output is presented in more detail. One day in the month of May for HU3 was chosen. Figure 8.7 shows the solar irradiation on the tilted and south oriented collector. The diffuse and direct radiation on the collector represent the total irradiation, which was converted with the collector efficiency to the useful process heat for the cold stream. For the given day, the collector efficiency varied between 35 % and 70 %. During dusk and dawn the irradiation and irradiation angle were not sufficient to be utilised.

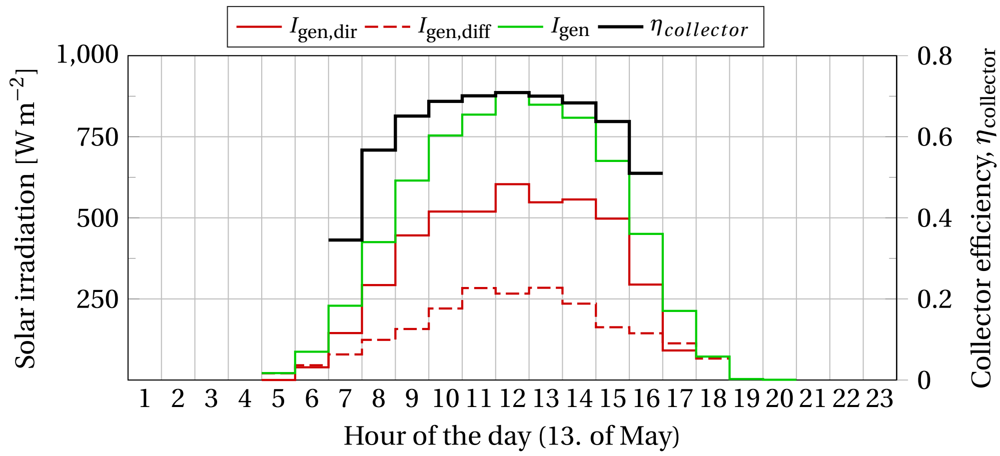


Figure 8.7: Solar irradiation and collector efficiency for one day for HU3.

In Figure 8.8 the energy balance for heating the cold stream is shown for each hour of the day. The total heating demand was 1575 kW of which more than half was covered by solar energy during noon. When considering the temperatures for each hour as shown in Figure 8.9, it can be seen that the solar stream preheated the process stream until up to 70 °C. While solar irradiation was available, the storage tank temperature increased from 54 °C to 59.5 °C at 4 pm. The temperature was then sufficiently high to preheat the process stream, when there was no more solar irradiation. The process stream was preheated to approximately 55 °C. On an annual basis, the mean collector efficiency was found to be 49.7 % for HU3 and 46.9 % for HU5.

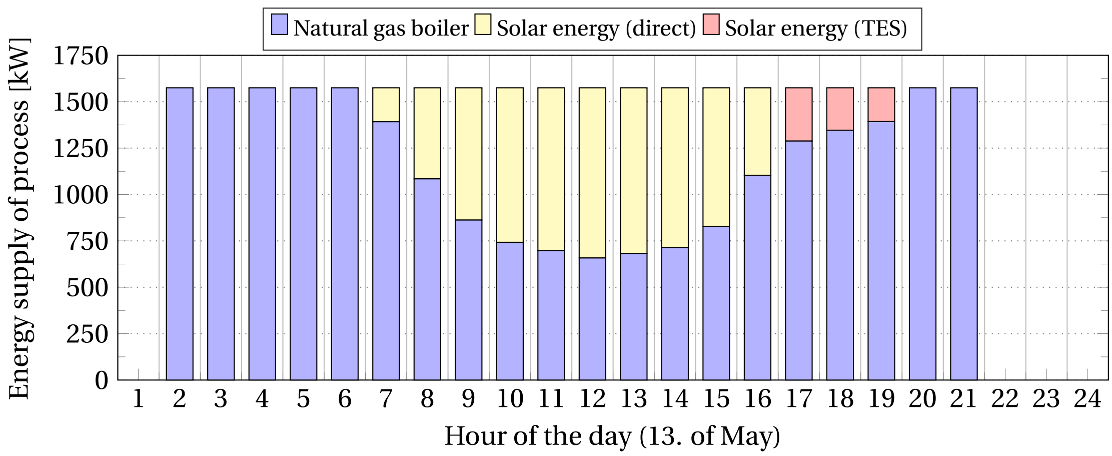


Figure 8.8: Energy balance heat supply to the process stream for one day for HU3.

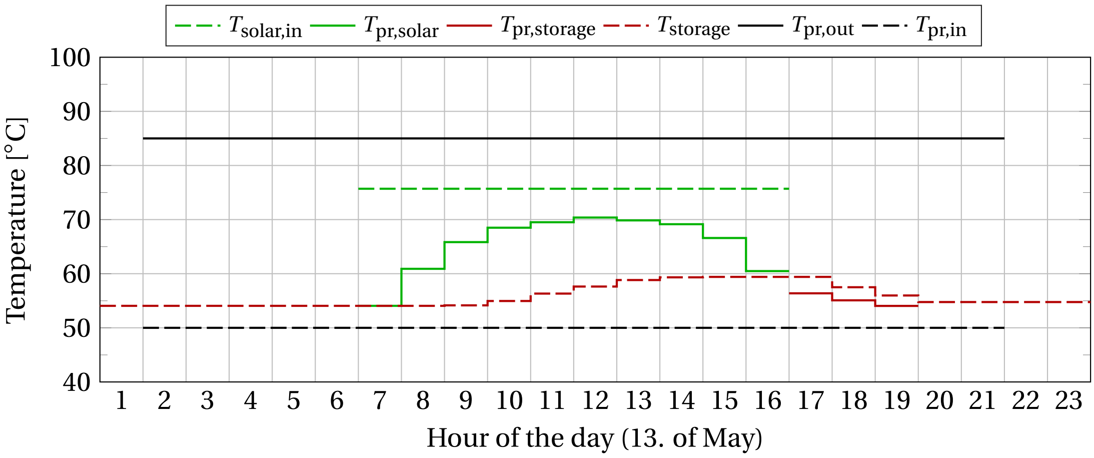


Figure 8.9: Temperatures of the solar and process system for one day for HU3.

Uncertainty and Sensitivity

The uncertainty analysis was performed for HU3 and HU4, which had the best economic performances. The MC simulations were performed with 200 samples, which had shown to have stable results. The values for solar area (A_{solar}), tank volume (V_{TES}) and solar outlet temperature (T_{solar}) were set to the optimal values found in the previous section. Table 8.8 shows the mean, standard deviation and 95 % confidence interval for the most important model outputs.

Table 8.8: Summary of the results for the uncertainty analysis with 200 samples, showing the mean model output, standard deviation and 95 % confidence interval for the most important outputs.

		C_{system} [k€ yr^{-1}]	PbT [years]	NPV [k€]	SF [%]	Q_{solar} [MWh yr^{-1}]
HU3	Mean	1184	7.6	930	9.5	1186
	Std. Deviation	239	1.8	490	0.7	93
	95 % Confidence	469	3.6	961	1.4	182
HU5	Mean	6569	12.5	274	1.7	1054
	Std. Deviation	1511	2.8	457	0.1	83
	95 % Confidence	2961	5.5	895	0.3	163

The standard deviation of the annual costs and the payback time was approximately ± 25 % of the mean value, while the 95 % confidence interval was twice the range. The NPV had a much higher deviation from the mean. In addition, the mean value of the NPV was higher than the optimal value found in the previous section. This was due to the lifetime, which had a mean of 22 years in the MC simulations as a result of the gamma distribution. The results of the energy balance had a considerably smaller standard deviation, as they were not impacted by the high uncertainties of the cost calculations.

The solar fraction of HU3 was almost 10 %, while the one of HU5 was less than 2 %. With the upper bound of 2000 m^2 active solar collector area, it was thus not possible to replace a significant part of the heating demand of the whole factory. Both systems had the same collector area, but the annual solar energy used was almost 100 MWh less for HU5. This was due to the higher solar collector outlet temperature and the thereby decreased efficiency.

Table 8.9 summarises the five most important parameters found with the two sensitivity measures for the annual costs and the solar energy supplied to the system. For the costs, both methods identified the natural gas price (1) and natural gas price increase (2) as important. The inflation rate (6), lifetime (7) and boiler efficiency were other important parameters. For the solar energy supplied to the system, the optical solar collector efficiency (21), first thermal loss coefficient (22) and the incidence angle modifier (20) were found important. It has to be noted that the SRC has several type I errors (identifying a non important parameter as important). In the solar energy supplied, for both HU3 and HU5, economic parameters were the 5 most important ones. Though these values did not influence the amount of solar energy delivered. It is thus advised not to follow the SRC for values below 0.1 in this case.

Table 8.9: Ranking of the model input parameters based on the outcome of the two different sensitivity analyses. The ranking annotation refers to the parameter numbers from Table 8.6 and 8.3).

	HU3				HU5			
	C_{system}		Q_{solar}		C_{system}		Q_{solar}	
	SRC	μ^*	SRC	μ^*	SRC	μ^*	SRC	μ^*
1	2 (0.7)	2 (0.62)	21 (0.95)	21 (0.97)	2 (0.68)	2 (0.75)	21 (0.94)	21 (1.02)
2	6 (0.37)	7 (0.54)	22 (0.17)	22 (0.23)	1 (0.39)	7 (0.62)	22 (0.20)	22 (0.17)
3	1 (0.35)	1 (0.52)	20 (0.10)	20 (0.08)	6 (0.37)	1 (0.5)	20 (0.07)	20 (0.07)
4	7 (0.32)	6 (0.37)	12 (0.05)	19 (0.02)	7 (0.36)	6 (0.36)	8 (0.04)	19 (0.02)
5	17 (0.14)	17 (0.12)	3 (0.03)	23 (0)	17 (0.14)	17 (0.14)	26 (0.04)	23 (0)

When investigating the impact of the input parameters on the solar fraction SF, the same parameters as for the Q_{solar} were identified as important, as presented in Table 8.10. The parameters for the payback time were different than for the annual costs. Parameters influencing the costs (28) and performance (21) of the solar collector were important for HU3. In the case of HU5, the cost factor for the heat exchanger (13) were found as additionally important due to the large size of the air to liquid heat exchanger. The linearisation of the MC simulations was further possible to the necessary degree, as can also be seen in Appendix C.2.1. Additional parameters found with the Morris Screening are presented in the Appendix C.2.2, as well.

Table 8.10: Ranking of the model input parameters based on the outcome of the two different sensitivity analyses. The ranking annotation refers to the parameter numbers from Table 8.6 and 8.3).

	HU3				HU5			
	Payback Time		*SF*		Payback Time		*SF*	
	SRC	μ^*	SRC	μ^*	SRC	μ^*	SRC	μ^*
1	2 (0.63)	1 (0.5)	21 (0.95)	21 (0.97)	2 (0.68)	2 (0.54)	21 (0.95)	21 (1.03)
2	1 (0.33)	2 (0.48)	22 (0.17)	22 (0.24)	1 (0.39)	1 (0.43)	22 (0.2)	22 (0.17)
3	21 (0.32)	21 (0.41)	20 (0.11)	20 (0.08)	13 (0.33)	21 (0.39)	20 (0.07)	20 (0.07)
4	28 (0.3)	7 (0.33)	12 (0.05)	19 (0.02)	7 (0.23)	7 (0.38)	8 (0.04)	19 (0.02)
5	7 (0.21)	28 (0.22)	3 (0.03)	23 (0)	28 (0.22)	13 (0.25)	26 (0.04)	23 (0)

8.4.5 Summarising discussion and conclusion

The hourly simulation steps, allowed a precise modelling of the system, however this resulted in high computational times for the optimisation. It was shown that two streams were economically suitable (NPV > 0) for solar thermal process integration, even with Northern European climate data. The air heating to the spray dryer showed an acceptable economic performance, while preheating the milk into the evaporator proved to be even better. Both streams had a high heat capacity flow rate and a high number of operating results, which allowed to install a large solar collector area (economy of scale) and the possibility to offset most heat during summer, with relatively small storage sizes.

Though the case study indicated that the integration of solar thermal energy to a milk processing line is economically feasible and can result in significant savings, some model limitations should be considered. The cost functions did not account for the piping between the actual placement of the cold stream and solar collector array. Generally, the varying return temperature to the solar collector should also be accounted for, which would result in a higher solar yield. The detailed modelling of the solar irradiation, allows the model to be easily used for other locations and solar array settings (tilt angle and slope). The solar heat generated per square meter collector area was 0.53 MWh per m^2 for HU3 and 0.59 MWh per m^2 for HU5, which is slightly higher than the 0.5 MWh per m^2 stated by Danish Energy Agency [188]. This can be a result of the initial solar irradiation data being higher in this model or a higher supply temperature assumed in the reference number.

The uncertainty analysis using Monte Carlo Simulations showed that the main model outputs, the annual operating costs and payback time, have an acceptable uncertainty considering the use of 19 uncertain input parameters. The payback time has a standard deviation of up to ± 3 years which could be acceptable for a first decision. In contrary to the economic results, the energy balance of the system has a low uncertainty. The amount of solar energy directly used by the system (SF = 9.5 %) has a 95 % confidence interval of only ± 1.4 %-points. This also highlights the uncertainties within finding accurate data for costs, compared to technical specifications and solar data. As a result of the sensitivity analysis, it can be further seen that the most influential parameters on the feasibility (payback time and annual costs) are primarily of economic nature. Based on the identified parameters, a more precise price for the solar collectors should be found and the assumptions towards the natural gas prices should be re-evaluated.

8.5 Discussion

A simplified case study of the dairy factory was used, which presents some limitations. A basic degree of heat recovery was assumed to be already present in the base case (R1, R2 and R3), some factories might however already have stream H1 and C3 integrated or a preheating of the drying air.

The evaporation unit was not included. The inclusion of the evaporator would not have impacted the outcome of this study, but could perhaps presented additional optimisation options. As shown in the previous chapter, the evaporators are usually equipped with TVR and MVR units, which could not be replaced with any hot stream in the system. A separate analysis of the optimal configuration of TVR and MVR under different prices for natural gas and electricity would be relevant.

For the heat exchanger network and heat pump integration, the time-wise mismatch between hot and cold streams was not considered. As can also be seen from the operating hours in Table 8.1, the dairy factory could be split into the milk treatment part and evaporation/ drying part. Matches between these two parts, might require thermal storages for balancing the loads. These are expected to be small as the spray dryer is operating almost continuously throughout the year.

The economic evaluation allowed to assess the private-economic feasibility of the solutions. While the cost correlations have uncertainties, which have been accounted for in the uncertainty and sensitivity analysis, some issues remain. The costs for the heat exchangers were found to be very high for small heat transfer areas (below 100 m^2). Though the correlation was supposed to be applicable in the range from 10 to 10000 m^2, better cost correlations for small areas could be used. This leads, in the case of the heat pump to a significant overestimation of the investment costs.

It was further found that the price of natural gas and its increase during the project lifetime had a great impact on the results. The economic viability of the solar thermal system depended strongly on an increase in future natural gas prices. The assumptions of high natural gas prices must not be necessarily true, especially for countries with large natural gas reserves. The values used in the model, should be chosen more carefully.

With respect to the solar system, a technical lifetime of the solar collectors of 20 years was assumed. The lifetime is usually stated with 30 years. The salvage value of the solar system could thus be included in the analysis or, alternatively, a 30 year lifetime. The main reasons for the lower lifetime was that the planning horizon of the industry will be short and factories revamps and production changes can occur on the long run.

The integration of the heat pump was further found promising, but is also dependent on increasing natural gas prices. In addition, the price for electricity and its increase add additional uncertainties. The use of ammonia as a working fluid showed good results. Other works show that the performance of the heat pump could be improved by using zeotropic working fluids, which are particular suitable for drying applications [289].

8.6 Conclusion

In this chapter a simplified version of the dairy case study, introduced in Chapter 7, was optimised with respect to its energy use and operating costs. This optimisation consisted of three elements, heat integration and design of a heat exchanger network, integration of heat pumps and use of solar energy for process heating.

The most cost-effective and largest saving potential in the dairy factory was found through heat integration. This was accomplished through the use of excess heat (drying air and condensate) and the integration of new regenerative heat exchangers. The use of mathematical programming has proven helpful to find the optimal network, however for the small problem a heat exchanger network could have been designed by hand. After the heat integration, heat pump opportunities were evaluated, which appeared promising and could cover most of the cooling load. A more detailed technical planning of these configurations is necessary. In particular, the supply of the remaining cooling demand, need for thermal storages and a single utility solutions for all hot streams could be interesting. The heat pump result is thus only indicative.

Modelling wise, the most effort was placed on the solar energy system. The created model is universally applicable and only requires horizontal global and diffuse solar radiation data. The computational time of the model should be reduced by creating representative time slices to avoid annual simulations. For two cold streams, the use of solar energy was found to be economic feasible, but having high payback times. The economic performance depends to a high degree on the current hot utility costs (natural gas price, boiler efficiency).

9 Barriers for energy efficiency and excess heat utilisation in the industry

This part presents a summary, review and discussion of barriers and drivers for the implementation of energy efficiency measures within the industrial sector and highlights the most applicable ones for excess heat utilisation. In order to apply the results of the literature review to the case of Denmark, first a summary of the most relevant policies impacting industrial energy use are given. Then, possible barriers in Denmark are identified based on literature and interviews, which are discussed at the end.

9.1 Introduction

The work performed in the preceding chapters showed that there is a potential for excess heat recovery in the Danish industry and that their are opportunities to reduce the energy use at industries through energy efficiency measures. A large fraction of these potentials and many measures were found to be cost-effective. However, industrial firms do not always implement these cost-effective energy conservation projects. The reasons are manifold and can be partly explained by market failure, non-market failure, behavioural and organizational theories [14, 313]. A number of studies have identified a gap between implemented and existing cost-effective energy efficiency project as summarised by Cagno et al. [313]. This is also referred to as energy efficiency gap.

The overall objective of this chapter was to determine and discuss reasons for not all cost-effective energy efficiency opportunities being implemented in the Danish manufacturing industry. This was done by analysing and reviewing findings and opinions from the literature. A particular focus of this analysis was the case of excess heat utilisation, both internally and externally, and how the findings relate to Denmark. As Denmark was used as a case study, also governmental support mechanisms, incentives and opinions form decision makers were summarised and analysed. To achieve the object the literature findings were complemented with empirical results for the case of the industry in Denmark. This was done by interviews with relevant persons from the industry. The findings of this analysis were used to discuss

9.2 Method

In order to determine possible barriers and drivers for the implementation of energy efficiency measures and utilisation of excess heat in the industry and to assess their significance and applicability to the Danish industry, the following method was applied.

First a review of barriers to energy efficiency and their classification was performed (Section 9.3). A more detailed review was done for the manufacturing industry and excess heat utilisation. The findings were summarised in the form of the most relevant barriers.

Secondly, in order to relate the findings to Denmark an overview of taxes, policies and subsidies directly impacting the implementation of energy efficiency measures in Denmark was established (Section 9.4). This also included a review of the efficiency of the Danish framework.

Based on the findings from the literature possible barriers which are thought to apply to Denmark are summarised and put into context with a theoretical case study and compared to opinions from key actors in Denmark. At the end the results of a survey, using questionnaires and semi-structured interviews are presented. The developed case study in Section 9.5 was based on the barriers found in the literature, in particular barriers used by [179, 314–316]. The design of the questionnaire and interview was adopted from [314, 316, 317].

A majority of the studies found in the literature (see Table D.2)determined barriers to industrial energy efficiency measures based on a multiple case study approach. These case studies were most of the time conducted with questionnaires and interviews, often with a combination of both. The method and recommendations for the design of case studies was elaborated by Yin [318]. He defined the scope of a case study as *an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and context are not clearly evident.* To this definition a technical one was added: *The case study inquiry copes with the technically distinctive situation in which there will be many more variables of interest than data points, and one result relies [...] on multiple sources of evidence and benefits from the prior development of theoretical propositions to guide data collection and analysis....* He further elaborated that case studies are often wrongly seen as research strategies and should be hierarchically organised, suggesting case studies as preliminary strategies. Case studies can however be exploratory, descriptive, or explanatory and include both single and multiple-case studies.

9.3 Review of barriers to industrial energy efficiency

A literature review of barriers to industrial energy efficiency was performed in 2011 by Sorrell et al. [319]. The authors reviewed a total of 65 academic works and 95 studies from organisations, all focusing on the industrial sector. The self-proclaimed aim of this work was to identify the nature, operation and determinants of different barriers. In the same year, Fleiter et al. [85] reviewed bottom-up energy demand models for industrial energy demand with a special focus on barriers to energy efficiency. As part of this work, a brief review of the barriers themselves and their classification was performed.

A further detailed literature review was undertaken by Cagno et al. [313] as part of a work developing a new taxonomy. As part of an interdisciplinary approach to energy efficiency in the industry, Thollander and Palm [16] gave an overview and in depth descriptions of theoretical barriers to energy efficiency. Most recently, Trianni et al. [320] summarised and collected empirical studies on barriers and drivers to industrial energy efficiency, based on contributions from other reviews. Johansson and Thollander [321] reviewed studies for Sweden to determine the most important barriers and create recommendations for internal energy management strategies.

A barrier is defined, according to Sorrell et al. [14], as a postulated mechanism which results in the organisation to oversee cost-effective energy efficiency opportunities. The classification and collection of the various possible barriers to energy efficiency is crucial for the understand the mechanisms in place. A taxonomy classifies the underlying concepts of principles creating the energy efficiency gap. A taxonomy has to account for interdependencies and interactions between single barriers. In the literature the taxonomy by Sorrell et al. [14] is widely used [85] and is described in detail in Section 9.3.1, as it includes the major barriers. An alternative taxonomy was developed by Cagno et al. [313] and aimed at overcoming the limitations with respect to interdependencies. A complete overview of the different taxonomies and additional approaches is presented in Appendix D.

9.3.1 Overview of barriers

Sorrell et al. [14, 314, 319] developed a widely used taxonomy, which includes a total of 15 barriers to energy efficiency. The taxonomy aimed to include the concepts of three areas of literature, namely economics, behavioural/ psychological theories and organisational theories. Therefore the barriers were classified into (i) economical, (ii) behavioural and (iii) organisational. However, each barrier overlaps across these groups [322]. It was therefore necessary to identify the most plausible cause on why an energy efficiency measure is not implemented. There are other taxonomies, which also aim to overcome some of the limitations in the Sorrell taxonomy. These studies are summarised in the Appendix D.1.

Economic perspective

The barriers from the economic perspective are sub-divided into non market failure and market failure. Out of these two, market failure is argued to give necessary but not sufficient reasons to for governmental policies.

Market failures Market failures, most relevant to explaining the energy efficiency gap, are imperfect and asymmetric information. Imperfect information can be divided into:

Lack of information: The industry might decide to invest into equipment on the basis of the lowest capital costs, while not knowing enough about the operating costs.

Cost of information: The industry might need to invest into information about energy saving opportunities (e.g. external experts). These costs might stop industries to gather all available information and take them into account for their decision.

Accuracy of information: Information of new equipment might tend to exaggerate performance or is biased.

Imperfect information is particularly important for energy services. For once, new equipment is purchased infrequently and the performance cannot always be evaluated directly before and after the installation. In addition, the changes in technology are often quick, when compared to the frequency of the purchases. This imperfect or asymmetric information can be divided into:

Adverse selection: Adverse selection occurs when one party has private information, before entering into a contract to buy or sell. An industry might by reluctant to pay a higher price for a more energy efficient good, as they cannot see the additional value.

Moral hazard within principal-agent relationships in energy service market: Moral hazard describes that e.g. insurance companies are not able to monitor the behaviour of policyholder. The holder may act in an irresponsible way.

Split incentives are a very important barrier. One party may have good information on an interesting energy saving project, but cannot convince the other party. This is typically referred to as landlord/ tenant problem. Overcoming this barrier, e.g. with contracts, might often have high transaction costs eliminating potential savings. This barrier is common in the household sector, but also in the industry this occurs when buildings or equipment are leased. Across departments split incentives can also occur. The owner of the machine does not pay the energy bill or managers remain in office for a short period of time and would not get credit for long term savings. These split incentives can also be of organisational nature.

Non-market failures Market barriers or non-market failure, cannot be classified as market or organisational failures, as they are part of the real life decision making process. These forms of barriers do not justify governmental interference, as it might be rational to reject energy efficiency projects from a business perspective. The three most important barriers in this context are heterogeneity, hidden costs and risk.

Heterogeneity: This barrier describes that the obtainable energy savings from a technology maybe an effective investment for the average user, but different users tend to have very different characteristics (e.g. operating hours, base and peak load).

Hidden costs: Engineering-economic studies are probably not accounting for all benefits or for additional costs for a given EEM. The true efficiency potential can thus be overestimated. The hidden costs can be categorised into (i) overhead costs for energy management (e.g. costs for energy consultants), (ii) specific to an investment (e.g. additional staff for O&M) and (iii) loss of benefits due to an efficient technology (e.g. problems with noise or reliability of machines). Several more examples for these hidden costs can be found [14].

Risk: High discount rates applied to investments and the refusal of energy efficient technologies is a rational response to risks. The risks are divided into (i) external risks (e.g. changes in fuel prices), (ii) business risks (e.g. economic trend/ outlook of the business) and (iii) technical risk (e.g. unreliable technologies). However it is very difficult to quantify the impact of risk.

Access to capital: Another barrier to include is the access to capital, which for some might have costs, higher than the average return on the energy efficiency investment. Though it is argued that this is not a failure, as the market dispatches capital to the highest risk adjusted return, it most certainly presents an economic barrier. In the industry, restriction to the access of capital are often self imposed. Existing capital is for instance used for prioritised projects, which are often not energy efficiency related or capital is not used for low risk energy efficiency projects with rates of return exceeding the company limits.

Behavioural perspective

The economic barriers described above would result in economic efficient solutions with rational decision takers. However a divergence between rational and actual behaviour was found [323]. This means that only market failures and barriers are not enough to describe the energy efficiency gap, but behavioural aspects must be included. Sorrell et al. [14] divides these barriers into bounded rationality and the human dimension, which emerged from psychological studies.

Bounded rationality: It was introduced by Simon [324], who described the constraints on time, attention and the ability to treat information by an individual. It can be further divided into *substantive rationality*, which assumes individuals take decisions as shown by optimisation models, and *procedural rationality*. The latter includes the limitation in time, resources and so forth of persons taking decisions. With procedural rationality, industries are likely to make satisfactory decisions rather than investing time and effort in the search for the real global optima. It further means that due to named limitations, a company might rather invest in their core operation, i.e. production rather than energy services. Also it was shown that routines influence the decision making process, such as rule of thumbs, which present a comfortable simplification. The rule of thumbs can be for example, requirements to payback times.

The human dimension, as part of the behavioural literature derives from social psychology rather than economics [324]. Sorrell et al. [14] determined the following four barriers, which origin in the psychological literature.

Form of information: One of the economic barriers was the cost of information, but even if information is freely available it is often ignored. This requires information to be in forms which are usable by individuals (e.g. clear, simple, specific and personalised).

Credibility and trust: Besides the form of information, also the credibility of the information plays an important role. The perception of credibility depends on several factors, such as the origin, past experience with the source, recommendations from colleagues and many more. This credibility of information is of particular importance as energy services are often outside of the core competences of an industry and decisions rely on external information.

Inertia: Industries might consider previous energy savings as opportunity costs, but the investment into new measures are seen as cut-of-pocket-costs. New energy savings have a high degree of uncertainty, while continuing with the status quo results in predictable outcomes. Lastly, the individual will tend to minimise regret. All of this will make the organisation favour the current situation, rather than investing into new energy saving measures. People will avoid changes, as they are committed to what they are doing. This allows them to justify that inertia by downgrading of contrary information.

Values: When describing the energy efficiency gap, the values of the individual should be irrelevant, as decisions should be only taken based on an economic evaluation. In practice the economic evaluation only presents one element of the final decision. When deciding to adopt or not adopt energy efficient technology, environmental concerns may also play an important role. A manager with an ecological attitude may be more likely to allow investments in energy savings. In industries one has to further distinguish between personal and cooperate values, latter often defined and part of the work culture.

Sorrell et al. [14] concluded about the human dimension, that it offers some useful insight, which can be included in a barrier model. However, there is a strong relation of these barriers to imperfect information and bounded reality. It is thus necessary to evaluate which barrier concept creates the best explanation of the observed behaviour.

Organisation theory

Sorrell et al. [14] described organisational theory approaches to barriers as the least well researched and selected three concepts from organisational theory literature that seemed relevant to energy efficiency.

Organisational structure: The literature reviewed by Sorrell et al. [14] showed that organisational structure cannot be formulated as a barrier to energy efficiency in itself, it is clear that the organisations structure will limit the possible actions towards increased energy efficiency. The structure is not a casual mechanism, it rather provides a pivotal framework for understanding the way barriers work. The organisational structure can act as a kind of filter for the choice of technologies. The causes for this are a limitation of information, as well as power and resources.

Power: When considering the organisation of a company, the power to implement changes can vary considerably between individuals and departments. It is thus important when quantifying the barriers, to determine the level of power the person, responsible for energy efficiency, has in the organisation.

Culture: The concept of culture is similar to the values. Culture in itself cannot be classified as a barrier but can again explain why energy efficiency measures are not implemented. Organisations can be seen as small societies, with different believes, values and norms. The personal norms and visions of the top management can have a significant impact on the whole organisation. This means that the priority and importance of implementing energy efficiency depend on the organisations culture.

The taxonomy developed by Sorrell et al. [14], included 15 barriers to energy efficiency. The summary above presented 12 barriers, by merging values and organisational culture, bounded rationality and inertia and form of information and credibility and trust.

9.3.2 Barriers in different sectors and countries

In the following the most relevant studies analysing barriers of the industry for a specific country or of a specific industry are summarised. An overview of these and additional studies can be further found in Table D.2.

Pulp & paper industry in Sweden The study by Thollander and Ottosson [325] emphasised the non-adaptation of energy efficiency measures that are cost-effective, as defined by the company's criteria, and should thus be implemented. The authors developed a survey which was send to 59 mills and was supposed to be answered by the sites energy managers. The answered to the survey revealed that almost all respondents agreed that there was a discrepancy between the potential and implemented cost efficient measures. The largest barrier given by the respondents was the technical risk (e.g. risk of production disruptions). In addition, the risk was also given in general as the seventh highest ranked barrier. On the second place, the costs of production disruptions was given, which may be related to hidden costs.

Small and medium companies in Denmark The Danish Energy Agency conducted in 2015 a quantitative analysis of barriers to energy efficiency in SME in Denmark [316]. The aim of this study was to determine:

- The company's initiatives to energy efficiency, with respect to electricity and heat use, as well as transport.
- The energy efficiency measure planned for the near future.
- Motivation to invest into energy efficiency and driving forces to accelerate the investments.
- The company's organisation with respect to energy efficiency.
- The company's primary information channels for energy efficiency and experience with external consultants.
- The central challenges companies are facing to perform economic measures.

Around 850 companies answered the questionnaire of which 59 % had less than 9 employees and 14 % more than 250. Around 15 % of the companies were from the industry sector, which were overrepresented in the sample of large companies. The motivation to perform energy savings in the company was primarily stated as saving money (79 %), as part of natural replacements (43 %) and to protect the environment (34 %). When asked what stops the companies in investing and performing energy saving measures, the main reasons were economic: Too long payback times (41 %), too low rates of return (39 %), prioritisation of other investments (26 %) and limited access to capital (25 %). This was also in agreement with the indicators used by the companies to assess the profitability of an investment into EEMs. The payback time and the business case were by far the two most mentioned economic factors. Asked how long the payback time for an investment into EEM could be, the majority (27 %) stated up to 5 years. While 40 % required the investment to payback within 3 years.

Information about energy efficiency was primarily collected through the internet, but also business partners, networks, specialist and trade journals were mentioned by the interviewees. If consultancy was required, the companies primarily asked the utility companies, handyman, suppliers and installers. Only 20 % asked consulting engineers, but larger companies with more than 50 employees contacted external consultants more often (35 %). Also subsidies (as explained in section 9.4.2) were known by 45 % of the companies, while larger companies were more aware of this opportunity.

The reasons for EEMs being conducted in the previous 5 years were: they were profitable, some kind of investment had to be done anyway or because of environmental considerations. Energy efficiency measures were not invested in because they were either not relevant for the company or not profitable. Only 10 % stated the lack of information being the reason. In the companies opinion the implementation of EEM would be supported if the Energy Agency would make the options for subsidy for energy audits visible and provide more general information about energy efficiency, together with consultancy support. Also more accessible and easy to understand information could help.

Foundries in Sweden The existence of barriers and drivers to the implementation of EEMs in the energy-intense Swedish foundry industry was investigated by Rohdin et al. [315]. The study was carried out as a case study using a questionnaire send to 59 foundries, which had a response rate of 47 %. The drivers used in the questionnaire were established mainly during a workshop with industry representatives, while the barriers were taken from the literature.

The results showed, that although many of the enterprises had financial difficulties in the previous 3 years, the companies future only played a minor role as a barrier. Further almost all companies claimed that cost-efficient energy savings existed at the plant. The main barriers given by the companies were with the importance in descending order:

- Limited access to capital
- Technical risk (e.g. production disruption)
- Lack of budget funding
- Cost of obtaining information
- Other prioritisation for capital investments
- Possible poor performance of equipment
- lack of sub-metering.

The study further asked to rank sources of information by their credibility. This is due the high importance of information for the acceptance of energy efficiency investments. A high ranking was obtained for information from colleagues within the sector, staff at the association and consultants performing energy audits. The least trustworthy information ranked were governmental sponsored energy audits, product information from suppliers and information from power companies.

These results let the authors conclude that the largest barriers cannot be overcome by governmental energy policies. Instead it was suggested to promote company oriented policy instruments and advocating long term energy strategies encouraging energy efficiency investments.

Foundries in the EU The study by Trianni et al. [326] analysed the barriers to energy efficiency within the European foundry industry with one of the main purposes being the identification of relevance given to energy saving in the operation. The authors first created a list of operational difficulties and their related theoretical barriers, based on Sorrell et al. [14]. The study was carried out as case studies using semi-structured interviews and questionnaires. This allowed the authors to have more reliable information, due to a positive relation between interviewer and interviewee and thus a more detailed and in depth talk. Based on this, 65 case studies were established across Europe. The majority of participants had a medium size, produced cast iron and had conducted an energy audit. The total sample identified the following two main problems:

- Lack of resources (time and capital)
  - Lack of budget for funding
  - Other prioritisation for capital investments
  - Lack of time and other priorities
  - Access to capital
- Importance of continuous production
  - cost of production disruption
  - hassle and inconvenience
  - barriers related to the technical risk

A further interesting result of the analysis, showed that companies which had conducted energy audits previously, increased the relevance of importance of continuous production and cost of production disruption. Having conducted an energy audit before, made the companies more aware of the possible hassles already connected to establishing an overview of the energy use and efficiency options.

Overall all the study found the lack of resources and the fear of hidden costs (from disruptions in the production) to be the main barriers. However the importance of barriers is not homogeneous, as it varies with company size, complexity of the production, country and if an energy audit had been performed.

Ceramic, cement and lime industry in Belgium The study by Venmans [327] had a focus on the decision making process leading to investment in energy efficiency and aimed at evaluating the importance of different barriers. Further the relation amongst different barriers and environmental policies was to be found. The study was based on interviews with managers, as they were taking investment decisions. The interviews with 19 companies were based on semi-structured questions about organisational structure, risk, reliable information and capital availability. In total 53 energy efficiency projects were discussed, regarding the motivation for them and the barriers encountered.

The results showed the motivation behind investments into EEMs. Increasing energy prices were ranked highest, followed by the commitment of the management to an environmental policy, environmental image and voluntary agreements. On the other side, barriers to why EEMs were not implemented at all or earlier were, sorted by relevance: Other investments received prior financing, risk of low demand (fixed costs from measure which turn unprofitable at lower production), the technical feasibility was not studied beforehand, difficulties to find financing and the profitability was not studied before.

It was concluded by the authors that the barriers most important to management were the ones related to availability of capital. Further it was observed that companies found energy related projects very important and postponed cost-effective investments because of internal capital budgeting rules. Second most important were barriers related to the lack of information.

Industry in Sweden Johansson and Thollander [321] performed a review of the barriers to and drivers for industrial energy efficiency in Sweden. Taking origin in about 300 surveys conducted over a period of 10 years, the authors reviewed the barriers and drivers to give an overview of tools for energy management and recommendations for successful in-house energy management. Some of the barriers perceived as very important, as found across most of the studies, were

- Behavioural barrier: Other priorities for capital investments
- Organisational barrier: Lack of time or other priorities
- Economic barriers: Technical risk such as risk of production disruption and the lack of access to capital

One main conclusion from the article was that employees can be a very important driving force for the implementation of EEM, if they have real ambitions to improve the situation. Companies should thus give these employees credit for the work.

9.3.3 Barriers to excess heat utilisation

Some studies which explicitly deal with excess heat utilisation are summarised in the following.

Low grade heat in the UK A relevant study for the current work was performed by Walsh and Thornley [179], who analysed why industries do not perform mitigation options and highlight the most strategic barriers for policy intervention with respect to low grade heat utilisation in the process industry. The barriers were classified based on a taxonomy developed previously for bioenergy utilisation in Europe [328]. This work was based on experience and views of stakeholders, collected during a workshop where participants were asked to identify the key barriers to the adaptation of EEM in the thermal process industries.

The stakeholders identified the barriers connected to cost, location, technology performance and return on investment as the major barriers. Most of these barriers were in accordance with the literature. The main barriers with respect to low grade heat were:

- The location describes the mismatch between supply and demand, suggesting that internal process optimisation has been often performed and external users need to be located or connected. This barrier appeared to be specific to the process industry and low grade heat recovery.

- Lack of infrastructure appeared as an important barrier in the process industry, describing the non existence or quality of piping for heat transfer
- Barriers in the form of risk in the performance and technology for low grade heat utilisation were found in the processes need for continuous rejection of heat. If the heat is utilised, the risk of sufficient and continuous cooling not being available at all times might increase.
- Stakeholders also expressed the need for clear information on who would establish infrastructure for low grade heat utilisation. Further it should be clear how responsibilities are divided amongst the owner of the heat source and end-user.
- Environmental benefits, such as a reduction of GHG, will be often credited to the end user rather than the source of excess heat. This might lead the industry to choose other projects reducing environmental footprints.
- Another barrier was the lack of information about suitable end-users in the proximity of the source, as these end-users will already have an existing energy supply and will not be identified as potential customers nor have incentives to change their supply.
- External heat utilisation might create a *technology lock-in*, where its existence in itself becomes a technical barrier to future EEM.

In summary the lack of pipes and infrastructure was identified by the authors as the most strategic barrier in the process industry. To cope with this barrier, direct intervention within the industry by capital investment, reorganisation or legislation is required. Also investment partnerships for heat distribution with local institutions might help to overcome this barrier.

Adjusting legislation which allows companies to claim credit for other utilising their excess heat could also be a driver. An initiative for energy mapping could be an effective support tool for informing relevant players about the location of heat sources and users.

Excess heat recovery in Sweden The study of Viklund [180] aimed at analysing the impact energy policy instruments have on the industries incentive for recovering excess heat. By performing research interviews with industry stakeholders in Sweden, the industries views on excess heat recovery with respect to energy policies were analysed. The author used semi-structured interviews with a short pre-interview questionnaire. The interview had the main themes: background information, main policy instruments and need for new instruments. In total eight interviews were conducted.

The respondents defined excess heat recovery as the external utilisation for district heating, which was the line the study followed. The results of the work highlighted several barriers to the use of excess and discussed possible solutions, with respect to the role of policies.

- The lack of use for the heat was given as a major barrier to the utilisation of EH (e.g. lack of a nearby DH area or DH demand). This is in line with Walsh and Thornley [179] who determined location and infrastructure as important points.
- The use of bio-CHP and waste incarnation over excess heat in DH networks was pointed out as a possible barrier. Here regulations could give prioritisation to EH. On the other hand, some extensions to DH networks can be traced back to bio-CHP and waste incineration being used. This network extensions allow EH sources to be more likely to be integrated.
- Risk was also found a barrier, in particular the possibility of closing, relocating or changing the production. One proposed measure to counteract these risks was a heat cooperation organised by the municipality. Barriers or obstacles with DH companies were: uneven production, non-municipally owned DH, alternative heat supplying facility and the risk the company will close down.
- It was emphasised that energy systems must be seen as a whole, including the industrial system. This should be considered when creating new residential areas.
- A barrier was to find the possible match between two parties, which would initiate collaboration. It is important to know the input and outputs of each site, e.g. through energy audits.
- Programmes promoting energy efficiency were seen as a good driver, as it makes companies commit to allocate time and efforts on energy matters. This counteracts the barrier of lack of prioritisation of energy matters.
- Education and information on excess heat recovery was seen as very important.
- The companies further primarily worked on internal excess heat recovery, as this is the easiest option. However internal support, goals and policy instruments affected their work on energy efficiency.
- Access to capital was seen as another barrier. Energy efficiency project are in competition with production improvements which are the core business. Further, annual investment opportunities were stated as limited, with required payback times of 1 to 3 years. An opportunity here are reconstructions, were improvements to energy efficiency and excess heat recovery can be performed.
- Companies which deliver EH to DH, had received investment grants in some form. These grants helped or even only made the projects possible.
- Increasing energy prices, taxes or reduction in subsidies on energy put excess heat recovery on the companies agenda. However, if such taxes are only a financial burden it might reduce the competitiveness of the company and ultimately force its closure.
- An important realisation was for companies to discover that EH has a value. Especially as the external utilisation is also connected with costs (time and efforts) for the company. However, a barrier was that the respondents often felt that EH was undervalued.

Industrial excess heat in Germany Pehnt et al. [138] analysed the utilisation of industrial excess heat from technical and economic perspectives and how this utilisation could be politically implemented in Germany. As part of the report also the barriers and drivers were analysed, which were found during a workshop.

- **Structural barriers** were rated as particularly relevant. The workshop participants identified that a requirement of the internal EH utilisation, is that there is an additional user in the near vicinity. Though this is not a barrier in itself, the additional pipping for instance, increases the complexity and costs. Besides, also the identification and quantification of the potential users are difficult. The external utilisation also requires close by heat users. Furthermore the temporal profiles and temperatures of the supply and demand, determine the technical intensity for the utilisation.
- **Economic and administrative barriers**. Besides additional investment costs, caused by new infrastructure, the costs for finding and evaluating excess heat were often seen to not be proportional to the possible revenues. It was mentioned that there were high costs for the complex planning process (engineering and architects) of external EH utilisation, which are difficult to cover. The higher costs for investments in excess heat utilisation are often recovered during the lifetime, but often do not fulfil the companies more rigorous investment requirements. The required security of supply, for third party heat users was further seen as an important barrier.
- **Technical risk and core business**. Concerns regarding the safety for a continuous production during the installation phase of new equipment and the fact that EH utilisation is often not seen as the companies core business, were stated as barriers.
- The lack of **information** about excess heat potentials and utilisation technologies was seen as a major barrier. Companies often do not have specific employees who are familiar with energy efficiency technologies. This could be theoretically covered through external consultants, seminars or additional staff. However in practice a lack of time, money, motivation and prioritisation of other tasks will stop the gathering of relevant information. The company might also miss information of potential internal and external heat users.
- **Judicial barriers** were not given the highest importance by the participants. It was mentioned that challenges exist regarding billing, if the EH emitter is not the same as the user. Technical installations for excess heat recovery would be subject to environmental and constructions laws, which would increase bureaucracy and costs.
- **Values and motivation** of individual responsible for energy in the companies, can have a large impact on the outcome of possible EEM. Reasons for such behaviour were mentioned to be a lack of time, fear of technical advancements and other priorities.
- **Technical barriers and requirements for development**, have minor impact based on the participants. There exist technical challenges and possibilities for development, e.g. fouling in heat exchangers, but these can be often overcome with good engineering and new technologies.

Based on the identified barriers and several drivers of excess heat utilisation, the authors concluded that the activities as part of self organisation of the industry and existing frameworks were not sufficient. They suggested to improve the framework for EH utilisation based on four pillars.

The first one is about information and continuing education, such as creating experience exchange, excess heat markets and seminars. The second one considers economic incentives and the third one the creation of technical standards and administrative law. The last pillar concerns research and development, where the potentials should be studied and new technologies should be developed.

9.3.4 Concluding summary

As part of the literature review the most relevant articles and reports on barriers to energy efficiency measures in the industry have been summarised. The review highlighted the different taxonomies grouping the barriers, possible barriers in itself and the methods used to describe the importance of individual barriers. The most widely used taxonomy found across the reviewed articles is the one developed by Sorrell et al. [14], which is often used in the exact or slightly modified form. Other taxonomies are either inherited by Sorrell et al. [14] or take Sorrell et al. [14] as origin. The taxonomy by Cagno et al. [313] has several relevant elements, such as grouping by organisation responsible of the barrier.

Several studies focused on the industry sector in Europe. An overview of the studies summarised in Section 9.3.2 and some additional studies are listed in Table D.2. The majority of the studies used a multiple case study approach to find barriers and rate the importance of them. In many studies a combination of questionnaires and semi-structured interviews was used, with some studies having workshops or questionnaires only. It is argued that semi-structured interviews give the best results, as it is possible to follow up on statements and has a positive influence due to the interviewee and interviewer relation.

The barriers identified as important across the different studies varied. This can be due to the different countries, industrial sectors and company sizes the study was performed in. But also the different aims and scopes of the studies, had an impact on the results as some studies targeted to analyse e.g. the role of policies or energy management systems. It was however possible to identify some barriers as generally important: The prioritisation of financing other projects then EEM and, in general, the access to capital were found as important barriers in many studies.

The technical risk from implementing new EEM in the production was also often important, also being reflected in the hassle and inconvenience of implementing EEM being too high and simply energy not seen as a core business. Information about energy efficiency opportunities, was rarely seen as a major barrier to larger companies. Whereby this barrier was more important for small companies and for cases where EH could be utilised.

9.4 Energy taxes, policies and legislation in Denmark

This section describes some of the most important taxes, policies and legislation which impact the energy use in Denmark and affect the implementation of energy efficiency measures in the industry. The concepts described in the following were also implemented in the models presented in the subsequent chapters and is partly based on the report [T2].

9.4.1 Taxes

Danish taxes on energy were introduced after the oil crises in the 1973, which aimed at reducing the consumption and to increase the security of supply. A tax on carbon dioxide was introduced in 1992 to reduce fossil fuel use and their harmful environmental effects. In 2005 this CO_2 tax was followed by the European carbon emission trading scheme.

Energy tax

The generation of heat from a fuel or other energy source is subjected to taxes in Denmark. An overview of the payable taxes is summarised in the following based on PwC (Price Waterhouse Coopers) [212]. There is in general a tax on fuels, which is regulated for oil products in *mineralolieafgiftsloven*, coal products in *kulafgiftsloven* and natural gas in the *gasafgiftsloven*. For these fuels an energy and CO_2 tax have to be paid. In addition, depending on the composition of the fuel, a tax on NOx, sulfur and methane has to be paid. The use of electricity is regulated in the *elafgiftsloven*.

Companies are often eligible to get some of the energy taxes reimbursed, this also applies in some cases for the CO_2, NOx, sulphur and methane tax. For fuels used in processes, the majority of the energy tax is reimbursable. The CO_2 tax is not reimbursable in this case, except the company has the permission of CO_2 emissions (CO_2 quotas). For some special processes, such as chemical reduction in electrolysis or direct heating of metals and minerals, a full reimbursement of the energy tax is possible. Fuels used for space heating are generally not exempted from parts of the tax. A reimbursement of the NOx, sulphur and methane tax is usually not possible for companies. A company is eligible for a reduction in tax, if they have special equipment installed which reduces the emissions of these gases.

Some companies are subject to CO_2 quotas, which aim at reducing the emissions of GHG. Companies subject to CO_2 quotas are generally refineries, production and processing of metal, cement, glass, brick and paper companies, with a certain size. Companies which have CO_2 quotas can get the CO_2 tax reimbursed for the fuels used in in processes. Companies which are not subject to CO_2 quotas can only get the CO_2 tax for district heat used as process energy reimbursed.

Excess heat tax

The utilisation of excess heat can be subject to taxes and several cases were summarised [T2]. The amount of taxes to be paid and the possible tax shields vary based on the source of excess heat, the applied recovery technology and the sink [233, 234]. Companies in Denmark are in general obliged to pay a tax on recovered excess heat when the heat originates from a process and is used by a special installation for a non-process purpose. The tax on surplus heat can originate in the legislation, regulating the taxation of energy for process and non-process purposes. The aim of the Danish surplus heat tax is to secure that no speculation is made in order to avoid paying similar energy tax for similar energy uses. The tax on surplus heat is put in place to compensate for a missing tax payment when process excess heat is subsequently used for a higher tax category as e.g. space heating. Further it is to encourage the installation of efficient heat generation equipment.

Process heat for internal space heat If the excess heat from a process is used by the company to heat buildings, e.g. through adding the excess heat to the central heating system, a excess heat has to be paid. This tax only has to be paid for the utilised heat in the winter months. If the excess heat from a process is used in the same room as the process is located, no excess heat has to be paid.

Process heat for district heating (directly or via heat pump) If the excess heat is sold to a district heating company and the temperature level allows a direct heat transfer, the payable tax is the difference of the space heating tax and the process heat tax but not more than 33 % of the excess heat price paid by the district heating company. Furthermore, a tax reduction is obtainable when a heat pump is used. The taxable heat is then reduced to the difference of the excess heat and twice the electricity needed, meaning only the heat produced at the COP above 3 is taxed. If the excess heat is sold to a district heating company and a heat pump is required, the amount of taxable sold heat is reduced by the electricity used multiplied by a factor of three. However the electricity used by the heat pump is taxed at the rate of electricity used for space heating. This adds the Public Service Obligation, electricity tax for space heating and the fee for the TSO to the net electricity price.

Electricity generated from excess heat The electricity generated from excess heat has no energy tax, as it currently is for all fuels. There are environmental taxes (e.g. NOx and sulphur) for burning of fuels though. Taxes only occur for the use of electricity and if the electricity is generated using renewable sources, tax credits of up to 20 € MWh^{-1} can be applicable.

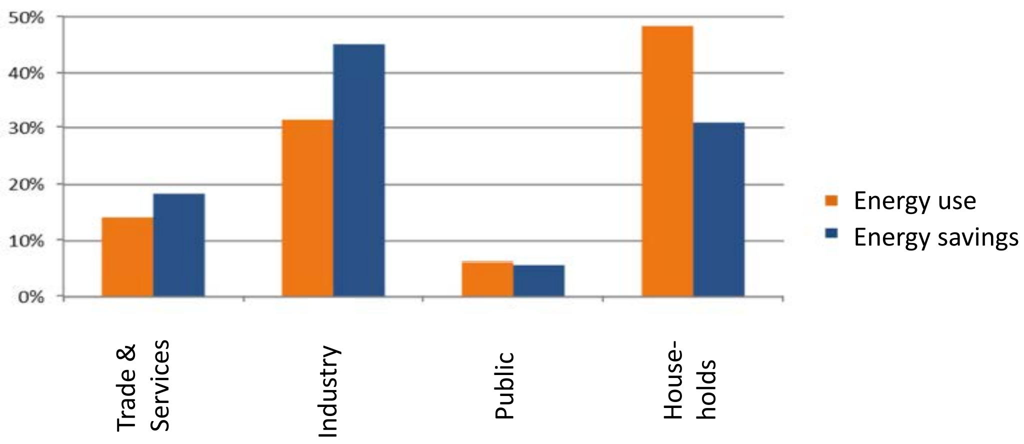


Figure 9.1: Distribution of energy use and energy savings in 2015 [329].

9.4.2 Subsidy

Since 2012 an agreement between the network and distribution companies within the fields of electricity, natural gas, district heating and oil and the minister for energy, utilities and climate exists regarding for the companies energy savings efforts. As part of this agreement which was revised in 2016 [211], the network and distribution companies committed to perform energy savings at end-users. This usually happened in the form subsidies paid to the end-users. The framework and conditions were set up in voluntary agreements. Over the period 2006 to 2016 a total of 76.5 PJ were recorded, overpassing the aim of 72.8 PJ for this period [329]. There was however and adjustment of the committed aims in the period 2013-2015. In the latest agreement the annual savings should be 10.1 PJ [211].

The majority of the savings were found in the manufacturing industry, followed by households, trade and services and the public sector. An overview of the distribution of energy savings compared to the share of energy use amongst these sectors is shown Figure 9.1. The industry sector had an over-proportional share of savings compared to their share in energy use, indicating cost-effective savings were possible.

The majority of the realised energy savings in 2015 were found in descending order as replacement of old boilers, process equipment, heating utility, thermal envelopes for buildings, lighting and ventilation [329].

There has been criticism of the execution of this subsidy system. The states and governmental audit criticised that the reported energy savings were not sufficiently verified [330]. Despite there being errors in 27 % of the controlled energy saving projects in 2013 and even 43 % in 2015, the controls were not extended. Further did the ministry not sufficiently follow up on this errors and if they were corrected in the reported energy savings, nor if there was systematic misuse of the system. It was further criticised that one third of the energy savings were obtained in households, despite reports suggesting that those savings do not give a socio-economic benefit.

9.4.3 Energy audit (Energisyn)

Large companies have the obligation to perform energy audits as stated by the European Parliament [331]. In Denmark these audits are referred to as Energisyn and are mandatory for large companies[1], who have to perform them every 4 years. These energy audits have to follow the EN ISO 50001(Energy Management Systems) or EN 16247-1 (Energy Audits) or EN ISO 14000 (Environmental Management Systems). According to the Directive the energy audit should be a *systematic procedure with the purpose of obtaining adequate knowledge of the existing energy consumption profile of an industrial operation or installation, identifying and quantifying cost-effective energy savings opportunities, and reporting the findings.*

Several reports assessed the effectiveness and impact of Energisyn in Denmark. Jantzen et al. [332] used 236 energy audit reports for their analysis which aimed at (i) deliver data about energy saving potentials in large companies, (ii) propose recommendations to future changes to energy audit directive based on quantitative data and experience from the reports, (iii) provide data about costs associated with the energy audits and (iv) provide data for other policies and legislations. The manufacturing industry was covered with 90 energy audit reports, however results were presented either accumulated over all sectors or for a few subsectors in the manufacturing industry.
Out of the analysed reports, a total energy saving potential of 15.8 % was found for the current energy use of 5.1 TWh per year. These savings would require investments of 2,500 million DKK while resulting in annual savings of 500 million DKK. If the data from the 236 reports is extrapolated to all large companies, the savings were around 2.4 TWh per year. The highest annual savings were found in the food industry with almost 250 GWh per year.

The average payback time of the energy efficiency measures was 5.2 years, with around 1600 out of 2700 below 4 years. This indicates that there was a large potential for cost efficient energy saving opportunities in Denmark. If 4 years was used as the maximum acceptable payback time, as stated in several of the energy audits, around 63 % of the energy savings could be realised. The manufacturing industry was further found to have overall payback times below 4 years, except the chemical industry. It has to be noted though, that many reports included subsidies (as explained in section 9.4.2) in their economic analysis. The costs for performing the energy audit, were found for the majority of companies to be below 20 % of the possible investments.

Another report by Pedersen et al. [333] for the Danish Energy Agency analysed the companies experience and opinions with the mandatory energy audits. The reporter is based on interviews with 145 large companies conducted at the end of 2016. The interviews aimed at gathering information about (i) the experience with performing the energy audits, (ii) the

[1] Large companies are defined as having more than 250 employees, an annual turnover of at least 375 mio. DKK or a balance of at least 322 mio. DKK.

impact of the energy audits, (iii) satisfaction with the audit and plus in information, (iv) other topics relevant for subsidies and performance of audits outside of Denmark.
The results show that 92 % of the companies had already worked actively with energy efficiency before the energy audit. Most companies hired external consultants to perform the energy audits, where the cost for the audit varied amongst the sectors. The highest costs for the audit were found in the manufacturing industry (205,000 DKK). Around 72 % of the companies found that in some way, they obtained a better understanding of the companies energy use.

In total 15 % of the companies do not consider the proposed EEMs, as they prioritise other investments or the payback time is too high. Only 41% of the companies found the energy audit was worth the investment. The share in the manufacturing industry was slightly higher with 51 %, however less companies in the manufacturing industry (31 %) thought that they received a better overview of their energy use from the energy audit. The primary reason for finding the energy audit meaningful, was that it made savings visible and gave an overview of energy use. The majority of the undertaken and planned measures were replacing the current lights (low payback time and easy to perform). Around 6 % of the companies performed or thought of reducing excess heat and performing process integration.

9.5 Perspectives for Denmark

In this section several approaches to barriers for energy efficiency in Denmark, with an emphasis on excess heat are presented.

In the following the barriers and some possible solutions for the external utilisation of EH, in particular EH utilisation for DH, are presented and discussed. The barriers were based on three pillars. First the possible barriers are discussed based on a theoretic case study and how this case would be implemented in practice. Secondly, opinions expressed by key actors in Denmark on the EH utilisation is summarised. Lastly, information obtained from a few sample interviews and conversations is presented.

9.5.1 Industry overview

The implementation of energy efficiency measures and the recovery of excess heat, requires the investment in process equipment and the modification or extension of the industrial site. As some of the barriers are rooted in these required process changes, these theoretical changes can be used to describe some barriers, which are relevant for EEM, in particular excess heat utilisation.

Figure 9.2 shows a simplified industrial site, consisting of a thermal process (e.g. heating, distillation, evaporation), which is powered by an energy source (e.g. natural gas) which was prior converted by some technology (e.g. boiler or burner). The thermal process has three outputs, the first is the wanted one, namely the energy service provided to the product (e.g.

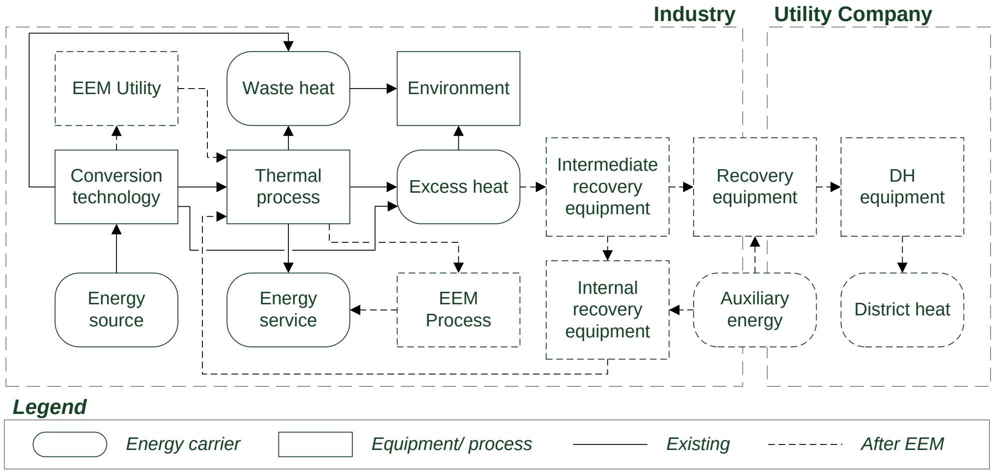


Figure 9.2: Implementation options and required investments of energy efficiency measures for process and utility improvements, as well as internal and external thermal excess heat utilisation.

separation, pasteurisation, melting). The heat rejected to the environment is excess heat and unusable waste heat. Similar, the energy conversion technology will create these three products, where the energy service is the heat supplied to the thermal process. The company can decide to reduce the amount of waste and excess heat generated, by improving the process or conversion technology. An investment in energy efficiency equipment is then performed, reducing the required energy input to provide the same energy service or the amount of waste and excess heat is reduced by improving the conversion technology or process.

In the case of excess heat, the heat can be recovered and used internally or externally. If the heat is used internally intermediate recovery equipment, such as heat exchangers, pipes and control electronics, are required besides internal heat recovery equipment such as heat pumps. Similar if the excess heat is used externally, the same types of equipment are used. In addition equipment on the user side are required, such as pumps and DH pipelines.

9.5.2 Possible barriers in excess heat projects

The external excess heat utilisation from an industrial site for DH requires generally two partners. In the following the barriers are discussed, which can theoretically arise if such a project is performed. The barriers are listed in order, at which they would occur when such a project is performed and are based on the barriers found in the literature. An overview of these barriers is shown in Table 9.1, which are based on Section 9.3 and own experience.

Table 9.1: Possible barriers to be encountered during all project phases, when using EH for DH.

Project Phase	Barrier Type	Barrier
Project Idea	Information	Information about EH and HD
		Credibility and trust
Project Intention	Organisation	Interest in changing status quo
		EH delivery not core business
		Long-term planning and perspectives
	Behavioural	Individuals taking initiatives
	Economic	Initial costs for feasibility study
Feasibility Study	Technical	Supply & demand match
		Technological development of HRE
	Economic	Energy prices
		Investment costs
	Behavioural	Form of Information
		Trust and credibility
Internal evaluation	Technical	Risk of production disruptions
		Technology lock-in
		Alternative technologies
	Economic	Economic outlook
		Security of supply
	Organisational	Hassle/ inconvenience
		Other priorities
Final agreement	Economic	Ownership model
		Revenue split
		Policies not clear (taxes and subsidies)
Project Implementation		

1. Phase Both entities (EH source and DH sink) have to be aware of each other and know about the others demand or supply, at first the lack of information and imperfect information has to be overcome. This barrier is on the one hand at the industry, who has to be aware that their production emits EH in the first place, that this EH can be recovered and that there are potential users (external or internal) in the vicinity [179]. At the same time the potential EH user has to have information about the possibility of using EH to cover their heating demand and that there is an EH source in the vicinity. These EH users can be located in another department of the company or outside of the company. Several possibilities exist to overcome this barrier, such as municipal information campaigns or excess heat exchanges [138]. For example in Saxony, a heat market accessible for free on the internet is available [2]. This barrier can be overcome on a municipal or national level by interventions of e.g. public institutions. However the significance of this barrier might be overestimated, assuming energy planners are

[2] Excess heat map (Abwäremeatlas) of the Sächsische Energieagentur GmbH (Energy agency Saxony) available at URL: http://www.saena.de/angebote/abwaermeatlas.html

aware of the opportunities of EH utilisation. It can be expected that municipal energy planners are aware of large industries in their region, as they will also present large consumers. However there can be issues of trusting the other entity, with respect to the available information and intentions. The problem might be therefore more located in the initiation of possible projects and the conduction of pre-feasibility studies as a first step.

2. Phase Assuming both partners are aware of the potentials, it is required that the organisations allow the follow up on the project idea. There must be individuals at each entity who want to pursue this option. This is in particular difficult as such a project has never been done before within the company and the cost-effectiveness of such a project is unknown. In addition, there must be a motivation to question and change the status quo. Assuming the production at the industry and utility company has been smooth, management has to be convinced that changing the current system will have long-term benefits without a direct financial or technical need. It is further required that both entities have a long-term planning horizon and take into account future benefits, as the projects can be expected to be complex and have a long planning and construction phase. Information material in the form of case studies of successful projects can be used to communicate the benefits and feasibility of these arrangements. However the source of this information must be credible and the information must be easily accessible and understandable.

Assuming both partners agreed to evaluate a possible cooperation, they will need to perform a feasibility study. This can be associated with high initial costs, e.g. external consultants and internal hours to map process streams and demands. Besides the high costs, also the distribution of these costs amongst the entities has to be regulated. Subsidies to the energy mapping or feasibility study could reduce this barrier. It could also be a requirement of the energisyn (Section 9.4.3) to evaluate the possibility of EH delivery to DH networks.

3. Phase Assuming the EH emitter and DH company agreed on performing a feasibility study, several possible technical and economic barriers can be encountered. The supply of EH and the demand for DH must match temporal. Thermal energy storages are possible, which increase the investment costs, but the EH must be large enough to be relevant for the DH company. On the other hand all EH should be preferably be accepted in the DH network, also in summer when DH demand is low. The characteristics of the EH source (temperature and media) will also determine if heat recovery equipment is available to use this EH. If temperatures of the EH are too low, a HP must be used which will most likely be technical possible. However if the EH source is contaminated, e.g. dust in gas or particles in water, there is a high risk for fouling and corrosion in heat exchangers. The industry might also have requirements for the DH return. If the EH originates from a process with cooling demand, the DH return must be cold enough to allow sufficient cooling.

The economic evaluation might reveal that the investment costs are too high (e.g. due to long

DH pipelines, large storages, high temperature lifts in HP) compared to the financial benefits. This is in particular a barrier if strict private-economic criteria (e.g. 2 to 3 payback times) are used and socio-economic benefits are not considered. Future energy prices might play an even more important role if electricity is considered for possible HPs. The future electricity price in this case would be in competition with other heat sources for DH. The risk resulting from this uncertainty might be too high.

The interpretation of the outcome of the feasibility, requires that it is presented in an understandable form. Furthermore, there must be trust in the performer of the feasibility study and the assumptions/ data must be transparent to be credible. This barrier is primarily depend on the external consultants, who must be able to clearly and openly communicate the outcome to both industry and utility. But also they must be transparent, so no mistrust amongst the two entities exist.

4. Phase Once it was clarified that the EH can be used cost-effective and the utilisation is technical possible. Both, the industry and utility company will evaluate the project internally. The industry might evaluate first the technical risks. The industry needs to remove EH from the process, which is done through stacks if EH is in the form of a hot gas, or through free cooling or evaporative cooling towers if a process stream is cooled down. If one of these technologies is replaced by heat recovery equipment, some control for the process is given to a third party. Ultimately the DH company will decide the degree of cooling, by the amount and temperature of DH return water available. This barrier can be overcome having back-up cooling towers, however this will increase investment costs and add fixed maintenance costs for equipment rarely used. Besides, the installation will create a technology lock-in. The industry commits to deliver EH which in some cases results from inefficient processes. By delivering EH, the option to increase efficiency of the process will not be there if it effects the investment of EH utilisation. But also changes to the production line will be more difficult to perform, e.g. the process can often not be changed to a modern one if it changes the availability of EH. There is also a risk for production disruptions during the production and initiation phase. Ultimately also the hassle and inconvenience of such a project will be relevant to some participants. A continued support from the consultants and material about similar cases, can help to take some of these perceived technical risks.

On the other hand, a major concern for the DH company will be the security of supply. One is the long term security of supply, as the risk of the company closing or reducing production will affect the DH system. Secondly the short term security of supply will play a role, if production disruption will reduce the amount of heat delivered to the utility. This is a great uncertainty which can be also described with imperfect information. The industry might be aware of the production disruptions and future development of the company but not share it. The DH will also evaluate alternatives to EH for the DH supply. The economic feasibility of the alternatives will also depend on taxes. As it is the case with biomass, which is tax free, and can often be used in modified existing plants, this might be the easy option to provide DH with low CO_2

emissions.

5. Phase Assuming the overall project is economically and technically feasible, the project partners made an overall agreement to pursue this project, several new barriers arise. At first an ownership model for the new equipment has to be found, as well as how revenues and costs are split. As indicated by Figure 9.2 the actual recovery equipment can be placed and owned by either the industry or the DH company. This ownership model can have an impact on the currently available subsidies (section 9.4.2). Furthermore a price for the EH has to be found, which forwards some of the revenues the DH company earns to the industry. The industry needs to cover their investment costs for the intermediate equipment, as well as fixed and variable costs for the delivery of EH itself. The EH has further a value, as it usually originates from the combustion of fuels, for which some of the costs can be allocated to the EH. These organisational issues, might not be a barrier in itself, as they can be solved. However support might be needed from an independent third party, such as consultants.

9.5.3 Opinions from key actors in Denmark

The taxes on both excess heat and the electricity used in heat pumps might represent a barrier to the use of excess heat for district heating in Denmark. This barrier was given as one of the main reasons for failed projects by industries, district heating associations and researchers.

The Danish district heating association *Dansk Fjernvarme* argued that energy taxes stop projects which utilise EH for DH, at the example of new data centres in Denmark [334, 335]. Large amounts of low temperature excess heat could be utilised with the use of electricity driven heat pumps. However it was argued, also by the local district heating companies, that the high taxes on electricity made the investments unprofitable [336].

For another case in Denmark, different reasons were given by local district heating company. It was argued that the connection costs, as well as the risk for interruptions in the supply were too high, to use medium temperature excess heat from a refinery for district heating [337]. This excess heat source would not have required a heat pump. Instead low temperature excess heat from municipal waste water was going to be used, which required a large heat pump. The local DH operators argued that the low electricity price outweighs the additional investment costs and security of supply. The same excess heat source from the refinery was in 2016 already ignored, when the decision for the renovation of a coal fired CHP plant to a new biomass fired heating plant was taken. As biomass was exempted from energy and CO_2 taxes, it was the more profitable options for the utility company [338]. This position was backed up during an interview with Professor Brian Vad Mathiesen from Aalborg Universitet, where he stated that tax free biomass stops investments into flexible and long-term solutions, such as use of industrial excess heat, heat pumps and geothermal energy [339].

The minister for climate, energy and building in Denmark on the other hand argued that a tax on excess heat was necessary, as it should avoid *false* excess heat to be provided to DH areas [340]. With *false* excess heat, inefficient processes or additional fuel input are meant, with the sole purpose of being used for space heating. He coincided, on the background that EH will often need heat pumps to become usable, that the tax on electricity can be a barrier if compared to the tax exempted biomass, which in the DH supply is a competitor to EH. He also stated that the EH tax might not be a fundamental economic barrier, but a rather confusing element acting as a barrier. The minister, district heating association and the local utility, agreed however on the necessity to adjust the electricity tax if a fixed excess heat tax is used. A fixed excess heat tax would simplify the tax system on EH, however will only allow profitable investments if the electricity tax is adjusted [335].

Based on the opinions expressed, it can be found that a fixed tax on excess heat can be perceived as an economic barrier if the heat is utilised with heat pump. The EH source might not longer be a cost-effective option, to tax exempted alternatives such as biomass. However an adjustment of the electricity tax for the use in heat pumps, as well as simple tax rules and clear communication, can reduce the impact of this barrier.

9.5.4 Opinions in the industry

In this section the results retrieved thorough the questionnaires and semi-structured interviews are presented. The questionnaires and interviews were used to get information about the experience with energy efficiency projects the participants previously had. Furthermore they were asked to state the importance of specific barriers in their opinion and experience. The questionnaire was sent to ten contact persons of whom two answered it and the interviews were conducted with two participants.

In the following several points raised by employees in industries, who were in charge of energy projects are listed. They are divided into barriers to energy efficiency in general and barriers concerned with the utilisation of excess heat in particular. No representative sample of industries and interviewees was available, the responses are thus from individuals similar to studies describing opinions raised in workshops.

General barriers stated for energy efficiency were, that the technology is not applicable at the site or the investment is not profitable. One participant, whose company operates several plants, noted that a major barrier are the decision makers in the organisation. They are not within the production themselves, which results in other benefits to the production through investments into EEM not being accounted for. Only the quantifiable and measurable monetary savings are used to take the decisions.

In a larger organisation it was also mentioned that money is allocated to other projects, not related to energy and that the prioritisation of investments resembles a political game. The importance of technical risks, such as of production disruptions and the hassle/ inconvenience of implementing EEM can be neglected. Also the available information is seen as trustworthy and credible (consultants, suppliers and exchange with other factories).

One major barrier to the utilisation of EH given, was the lack of appropriate technologies and technical constraints for the EH recovery. Though companies are generally aware of their excess heat (from ventilation, exhaust gases and boilers in the surveyed companies), the utilisation is seen to be technical challenging. These barriers are confirmed by consultants, who see EH recovery projects as complex and to require a high degree of engineering, even in the initial planning phase. For the external utilisation one barrier is seen in that EH delivery to DH is not the core business of the industry. The industry produces a good and do not want to expand their boundaries. They prioritize the core business over other investments and rather spend their time on production issues.

Barriers imposed by the behaviour from the companies, are protectionism with respect to information. As the EH will originate from some processes, it is necessary to share process and production data with third parties, to which the companies might be reluctant. The companies also require the production to be kept independent of the heat sink. However they are often willing to communicate changes in the production, which would result in changes in EH. As shown in Section 9.5.1 the EH emitting company will need to find an agreement with the DH company, to split revenues and an ownership model for investments. This was not stated to be a major barrier, under the conditions that the project profitability is high enough to give a *good deal* to both sides.

9.6 Discussion and conclusion

In this chapter, first possible barriers to and taxonomies for EEM in the industry were summarised, followed by a literature review of articles analysing barriers in the manufacturing industry in Europe. The relevant barriers which apply to a given industry depend besides the type of industry (e.g. manufacturing, energy intensity, type), on the country they are located in, the size and focus of the study itself. The financing of EEM is often found as an important barrier in the literature. This barrier can be due to the prioritisation of other investments or due to capital being unavailable. The technical risk of the EEM can also play an important role and missing information about the possible measures itself. While these barriers are generally important, they cannot necessarily be directly applied to Denmark and the Danish composition of manufacturing industries.

The second part of this chapter described the energy taxes and policies in Denmark. The sale of energy saving, as a form of subsidy, applicable for EEM was used often by the companies. Around 4 TJ of energy savings were realised through this subsidy, though it is unclear what share would have been conducted without this subsidy. The mandatory energy audits for large companies was found to be perceived with mix opinions in the industry, as large companies have generally control over their energy use.

In the last part, an analysis of the barriers to industrial energy efficiency and the utilisation of EH in Denmark was performed. This analysis was based on a generalised case using the literature review to find possible barriers for the external EH utilisation. An excess heat utilisation project can encounter several barriers during the project framework. While barriers can often be solved thorough communication and technical solutions, the initiation of the project due to the lack of knowledge is found as a limiting factor. The opinions on the barriers for the external EH utilisation showed that a barrier is seen in the current tax system. This barrier might however be not as high as stated by individuals, as they represent their organisations interest and often aim to increase profits. The number of project using EH for DH also shows that it is possible to perform projects with the current tax system. The opinions found during interviews, highlighted the technical and behavioural barriers for the external excess heat utilisation. It was however not possible to gather representative sample of industries and opinions. The responses thus have to be seen as opinions of individuals.

10 Concluding remarks

This chapter presents a summary of the findings presented in this thesis and recommendations for future research areas.

10.1 Summary of work and findings

In this thesis two main parts were considered. First an analysis of the manufacturing industry was performed, determining the efficiencies of the processes and utilities of different industry sectors. Based on this analysis the industrial excess heat and its utilisation potential with respect to the energy system was determined. The possible barriers to excess heat utilisation were shown and specific cases were analysed. For this analysis Denmark was used as a case study.

Second, different methods for the analysis of industrial sites were applied to a case study to qualitatively compare the applicability and outcome of the methods. A focus of this analysis was on the comparison of engineering and advanced thermodynamic methods. The methods were applied to the case study of a milk powder production factory.

10.1.1 Industry and excess heat analysis

First a summary of the findings with respect to the applied and developed methods is presented, followed by a summary of the findings specific to Denmark.

Methods

When analysing the industry it was found that the inclusion of the complete energy system and the accounting for the irreversibility of transformations, increased the significance and the interpretability of the results. In particular the comparison of different countries or industry sectors (e.g. dairy, cement or metal industries) is more meaningful, as a common basis with respect to the different energy carriers and their conversion is considered with these elements.

In a second step the amounts of excess heat were quantified. The process mapping used the energy end-use models created for the manufacturing industry, which allowed a detailed description of the excess heat with respect to temperature levels and processes. The THERM-CYC mapping relied on more aggregated assessments for processes on a sector level. This approach allowed the quantification of excess heat of all sectors in Denmark, but was limited with respect to the accuracy of the broad estimates. Though both methods are applicable to other countries, they were developed based on the available data for Denmark.

To find the possible utilisation potential of excess heat for district heating, an approach was developed which applied spatial, thermodynamic, temporal and economic elements to excess heat and district heating data. This included the temperatures of the district heating supply and return for each network, the seasonal and daily profiles for heating demand and excess heat availability and the location of industrial sites and district heating networks. With this approach it was possible to establish a potential for excess heat utilisation which was refined through these elements. This allowed to find amongst others the requirement for heat pumps, thermal energy storage and unit costs of district heat. The required input to these models is also available or can be generated for other regions. Some parameters, such as the price of excess heat, have a great influence on the cost effectiveness. This price is only hardly assessable, as it depends on agreements and the local situation.

Barriers to the use of energy efficiency and excess heat utilisation were established by performing a literature review of national and international studies, analysing the tax and subsidy system and creating a case study. Altogether, this resulted in several barriers which were identified to be probably relevant for Denmark as local conditions were included. To confirm these findings the case studies have to be extended to include more companies and district heating representatives. The barriers found throughput the literature, were however consistent with respect to excess heat, thus a good indication for overcoming them could be given. The following are the most important identified barriers for excess heat utilisation. The lack of information about possible opportunities is a limiting factor. If information is available, the risks associated with the creation of dependencies between the industry and district heating supply were possible barriers on both sides. The district heating operator wants a long term investment, while the industry wants flexibility in changing their production. The taxes and subsidies were found to be not an actual barrier. This was also confirmed by the case studies for excess heat utilisation, were in most cases the taxes on electricity and the amount of subsidy were not the most important parameters. However, taxes were perceived as important by both industries and district heating companies.

One way to overcome the barriers was to create a tool which allowed to identify and evaluate cases for excess heat utilisation, without the requirement of finding additional data other then what was previously established. This tool can be used to pre-screen possible projects and evaluate their economic viability. It was found that the results of such a tool can have a great uncertainty, of which the users have to be aware. By implementing a tool for the sensitivity analysis, the users could efficiently reduce this uncertainty by improving a few key input parameters. One of the important parameters was the excess heat temperature, which was uncertain due to being found in the sectoral mapping. If the temperature was close to the district heating supply temperature, a small change could mean a heat pump was required. A more precise estimate by the industry, when using this tool, could thus increase in certainty considerable.

Denmark as a case study

The conversion efficiency of energy within the manufacturing industry was analysed for Denmark. In 2012, the industrial sector was found to have had an energy efficiency of 80 % and an exergy efficiency of 40 %. When including the conversion efficiencies of fuels to electricity and district heat at the utility sector, these efficiencies dropped to 70 % and 30 % respectively. This indicates, that high temperature processes with a high amounts of excess heat should be targeted, as large quantities of this heat are recoverable. The use of district heat and heat pumps for process heating, where the temperatures allow it, would further improve the site efficiencies.

With the THERMCYC mapping it was found that the transport sector had an estimated 76 PJ of recoverable excess heat, the utility sector 58 PJ and the industry sector 48 PJ. This mapping identified a low temperature excess heat potential below 60 °C of around 80 PJ, primarily from cooling and refrigeration processes, condensate and from industrial processes. The high temperature potential originated from combustion processes and exhaust gases and was found between 160 °C and 260 °C. The excess heat potential of thermal processes in the manufacturing industry, as found in the process mapping, was to a large extent located in this high temperature range. The main excess heat sources were in the oil refinery, building material (cement in particular) and chemical and food industry. In total 12.7 PJ of excess heat were found for the manufacturing industry using the process mapping.

The spatial analysis of the excess heat in Denmark showed that there are some industry locations with large amounts of excess heat. These large sources were found at the locations of oil refineries and the cement production plant. It was further established that approximately 1.36 TWh of district heat could be supplied from excess heat created in the manufacturing industry, which corresponds to 5.1 % of the district heating demand in Denmark. Heat pumps were required to make 36 % of the excess heat usable, considering the current supply temperatures of the district heating networks. Though excess heat from the considered processes will not be a major source for district heating on a national level, it can have great significance for several district heating networks.

When considering the socio-economic costs of using excess heat, it was found that these costs have a weighted mean of 35.6 € MWh^{-1}. Large industrial sites were found to have generally lower costs for district heating, as the ratio of piping costs to the amount of heat delivered were low. In Denmark, a few large industries, dominated the results of usable excess heat potential.

The evaluation of several specific case studies and the creation of a tool for locating cases was developed for the use in Denmark. The analysed cases show that it is often cost efficient, from a private economic perspective, to deliver excess heat to district heating networks, other factories or to produce electricity. The final feasibility depends on a lot on the share of profits between the district heating company and the industry and the price of the obtainable in the local district heating area. The taxes for the use of excess heat were found to of relevance for the heating price when heat pumps with low COPs were used, but the temperatures and heat pump efficiency still remained the more important factors.

10.1.2 Industrial site analysis

First a summary of the findings with respect to the applied methods is presented, followed by a summary of the findings specific to the milk powder production.

Methods for the analysis of industrial sites

One of the aims of the industry analysis, was to compare the suitability of different methods for the analysis of industrial systems, with respect to their energy use and efficiency improvement potential. The background was to give recommendations to industry professionals on the benefits of advanced methods. At first an engineering approach was applied, in which process data is benchmarked to other industrial sites or best practices. The outcome of this analysis depends thus heavily on the experience of the analyst. There were no clear guidelines available and the possible saving potentials were not directly quantified.

Pinch analysis, as an established method for the analysis of industrial systems, allows the determination of the heat integration potential, thereby giving a target for minimum energy use. It also gives hints for the design of heat exchanger networks and the placement of utilities. The more systematic approach to pinch analysis was found to be an advantage to the engineering approach.

For the exergy analysis, a model of the industry system was created, while the previous analyses only required the process stream data (flow rates, temperatures and loads). With the exergy analysis it was possible to determine the exergy efficiency, exergy destruction of each component and the losses of the system. This allows to locate the most inefficient components, to compare similar components and analyse the waste streams. However, the actual improvement potential remained unknown. To account for the real improvement potential and to study the system in more detail, an advanced exergy analysis was performed. While the results gave useful insights, in particular the share of unavoidable exergy destruction, the application of the method was limited. These limitations arose from the production system not being flexible enough to perform such an analysis, due to product set-points and, in a thermodynamic sense, unnecessary components. For the analyst, the advanced exergy analysis requires the most work. It is necessary to take many assumptions and gather more data, besides multiple model evaluations are required.

Milk powder production as a case study

Based on the performed analyses it was possible to identify several inefficiencies and saving potentials in the milk powder production factory. With the engineering approach the possibility of extending the regenerative heat transfer is several pasteurising units was shown, as well as a possibility for heat integration. The pinch analysis showed that the factory is already highly integrated and no apparent measures for heat integration existed. The inefficiencies in the hot utility supply were however shown and several free streams were identified, for which heat recovery measures could be applied. The exergy analysis also showed that the hot utility is inefficient. Approximately 62 % of the exergy destruction occur in the boiler and burner. In the heat treatment section more than 50 % of the exergy destruction took place in the three heaters. The advanced exergy analysis showed that less than 10 % of the exergy destruction in the heaters is avoidable, while this share is even less in the hot utility. Improvements in the production system, would however increase the exergy destruction in the current utility. This could be avoided by using for example a heat pump, as an increase in the return temperatures from the production would increase the heat pumps effectiveness.

Based on a simplified milk powder production case study, the creation of a heat exchanger network, the use of heat pumps and solar energy was analysed. The technical and economic analysis showed that the cooling demand could be reduced by 58 % and the heating demand by 33 %. This target was also achieved by designing a retrofit heat exchanger network, consisting of 4 regenerative heat exchangers. For each of the remaining cooling demand, the use of a heat pump to supply process cooling and heating was evaluated. With investments of payback times below 8 years, it would be possible to almost cover all cooling requirements with heat pumps. The use of solar thermal energy was found to be profitable in two cases, namely for the heating of skim milk before entering the evaporator and the heating of drying air into the spray dryer. The payback times for these investments were 7 and 13 years, respectively.

10.2 Recommendations for future work

The excess heat mapping for Denmark in particular should be extended to include the energy use of the industry as used in the THERMCYC mapping, but with the level of detail as in the process mapping. Furthermore excess heat sources from data centres, supermarkets and storehouses should be investigated and added to the mapping in a high level of detail with respect to temperatures and amounts. The accuracy and level of aggregation of processes and sectors was found sufficient for the purpose of the analyses in this work. A higher level of detail in the excess heat mapping could be obtainable, through more detailed end-use models, questionnaires sent to companies and if access was granted, through energy audit reports (energisyn).

The analysis of excess heat utilisation by delivering it to the energy system in form of e.g. district heat has been shown to be feasible. A similar study could also address an increased use of district heat in the industry, taking into account the supply efficiencies, need for heat pumps and the district heat capacity of the networks.

Two major potentials for future work in the industrial process analysis were identified. First, the pathway of developing simplified methods for the analysis of energy efficiency opportunities could be followed and could lead to practical methods for analysing industrial systems with a minimum of data. Some work has been performed on this previously, in particular with respect to process integration, but further efforts are necessary. These simplifications become even more important if batch production is considered, as the process integration problems become highly complex.

Second, exergy methods haven been shown to be useful for the industry analysis. The lack of its application in mappings of industrial sites could be further analysed to identify the barriers. But also an exergoeconomic analysis of the process should be performed, to find system inefficiencies in terms of actual costs. These results could be easier communicated to the industry. The exergy-based analyses also require a lot of data and assumptions. The impact of the uncertainties arising from these assumptions should be analysed more thoroughly.

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A Excess Heat

A.1 THERMCYC aggregation

Table A.1: Aggregation of sectors and their NACE code for the THERMCYC mapping.

THERMCYC	NACE Code	Description
Industry	A	Agriculture, forestry and fishing
	B	Mining and quarrying
	C	Manufacturing
	G	Wholesale and retail trade...
	I	Accommodation and food service activities
	D	Electricity, gas, steam and air conditioning supply
	E	Water supply; sewerage, waste...
Construction	F	Construction
Transport	H	Transportation and storage
Buildings	J	Information and communication
	K	Financial and insurance activities
	L	Real estate activities
	M	Professional, scientific and technical activities
	N	Administrative and support service activities
	O	Public administration and defence...
	P	Education
	Q	Human health and social work activities
	R	Arts, entertainment and recreation
	S	Other service activities
	-	Households
Solar	-	Public
	-	Residential
	-	Agriculture
	-	Commercial

A.2 Industry aggregation

Table A.2: Industry categories and the associated industry sectors included amongst other in the process mapping. The european classification NACE and the Danish DB07 are included [48, 89, 90].

Industry Category	Industry Sector	NACE	DB07
Gravel & Stone	Extraction of gravel and stones	08	080090
Oil Refineries	Oil Refineries	19.2	190000
Food	Slaughterhouse	10.1	100010
	Diary Processing	10.5	100030
	Production of compound feed	10.9	100050
	Other food industry	10.89	100050
Sugar	Production of Sugar	10.81	100050
Wood, Pulp & paper	Wood Industry	16.2	160000
	Paper Industry	17.1	170000
Chemical & Pharmaceutical	Production of Industrial Gasses	20.11	200010
	Production of Enzymes	20.14	200010
	Other chemicals	20.59	200010
	Pharmaceutical industry	21.00	210000
	Plastic and rubber	22.00	220000
	Production of paint, soap and more	20.59	200020
Cement, Bricks & Rockwool	Production of Cement	23.51	230020
	Production of Bricks	23.40	230020
	Production of Rockwool	23.99.90	230020
Concrete products	Other concrete and bricks	23.69	230020
Asphalt	Production of Asphalt	23.99.10	230020
Metal	Production of Metal	24	24000
Metalproducts	Metalproduct Industry	25	25000

A.3 BBR aggregation

Table A.3: Aggregated groups of heat users and the associated use types [341].

Aggregated group	Use code	Use
Residential	110	Farmhouse
	120	Detached house
	130	Terrace house
	140	Block of flats
	150	Student residence
	160	Residential institution
	190	Other dwelling
Office/ service	310	Transport
	320	Trade and commerce
	330	Hotel and service
	390	Other trade
Culture/ public	410	Cultural building
	420	School
	430	Hospital
	440	Kindergarten
	490	Other public institution
Leisure	510	Summer house
	520	Tourism
	530	Sports
	540	Allotment house
	590	Other leisure building

A.4 Seasonal distribution of excess heat

Table A.4: Generalised seasonal distribution of the EH.

Industry Category	Seasonal Excess Heat Distribution			
	Winter	Spring	Summer	Autumn
Gravel & Stone	0.33	0.25	0.17	0.25
Oil Refineries	0.25	0.25	0.25	0.25
Food	0.25	0.25	0.25	0.25
Sugar	0.36	0.18	0.09	0.36
Wood, Pulp & paper	0.25	0.25	0.25	0.25
Chemical & Pharmaceutical	0.33	0.22	0.22	0.22
Cement, Bricks & Rockwool	0.25	0.25	0.25	0.25
Concrete products	0.38	0.25	0.13	0.25
Asphalt	0.00	0.25	0.50	0.25
Metal	0.25	0.25	0.25	0.25
Metalproducts	0.25	0.25	0.25	0.25

A.5 Profile comparison for district heating

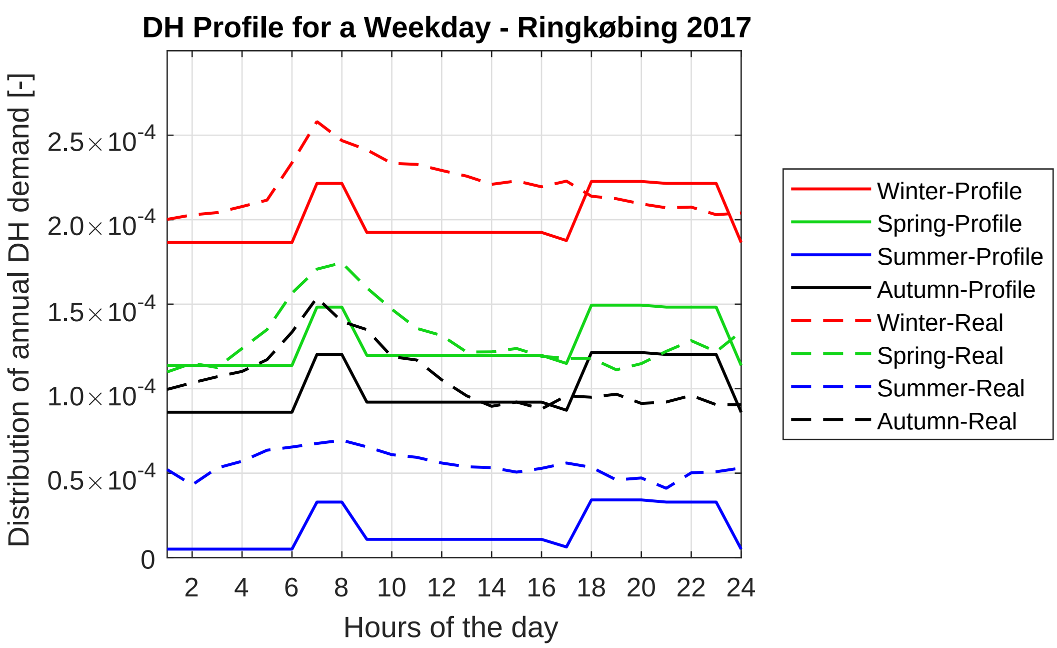

Figure A.1: Comparison of the artificially created hourly district heating profile to the one of Ringkøbing for weekdays in 2017.

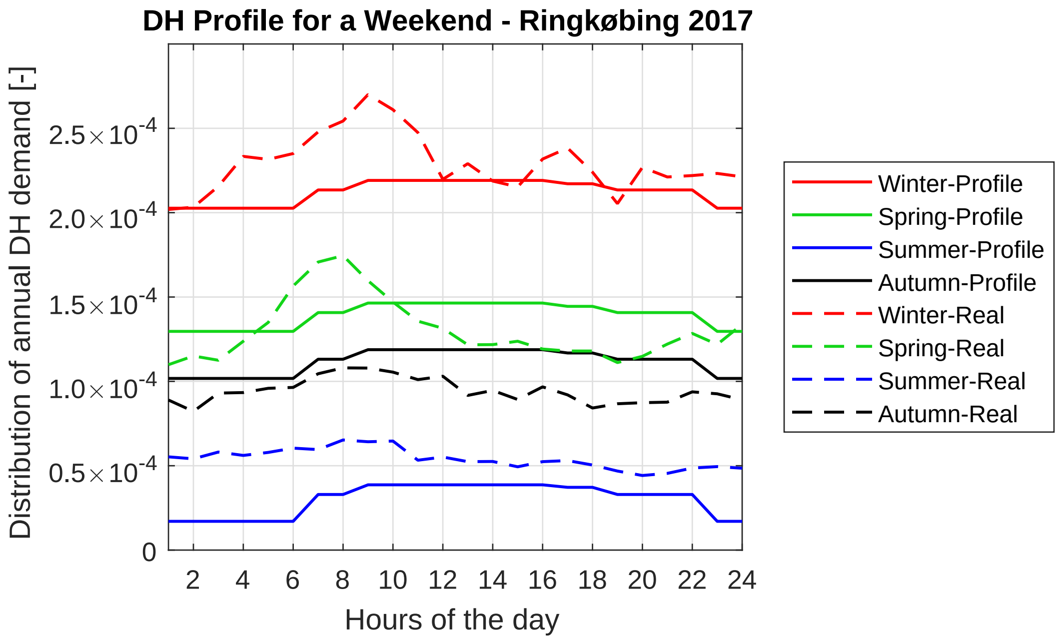

Figure A.2: Comparison of the artificially created hourly district heating profile to the one of Ringkøbing for weekends in in 2017.

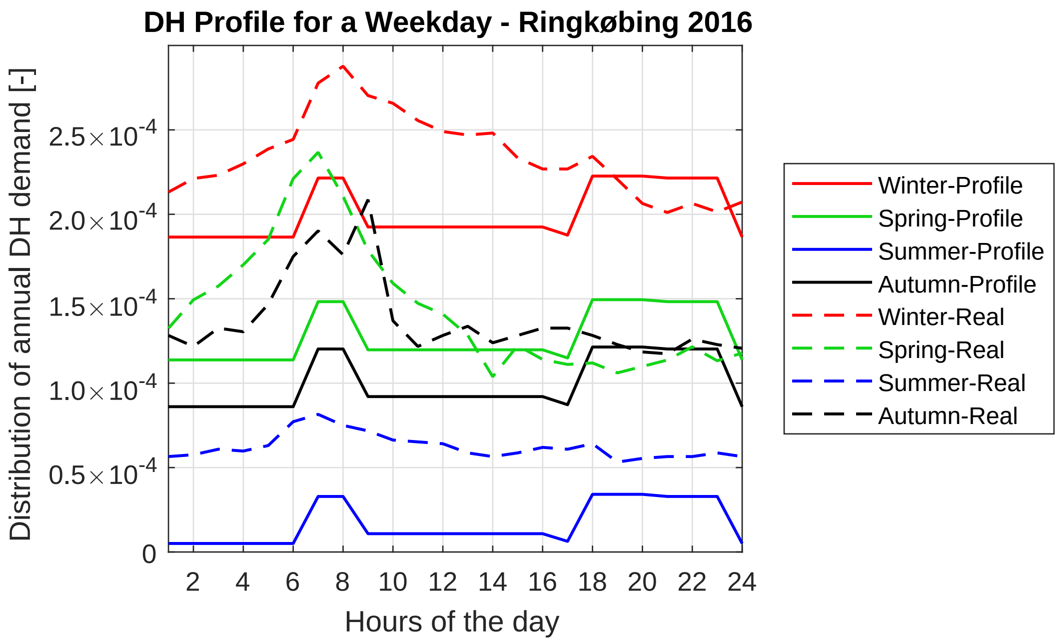

Figure A.3: Comparison of the artificially created hourly district heating profile to the one of Ringkøbing for weekdays in 2016.

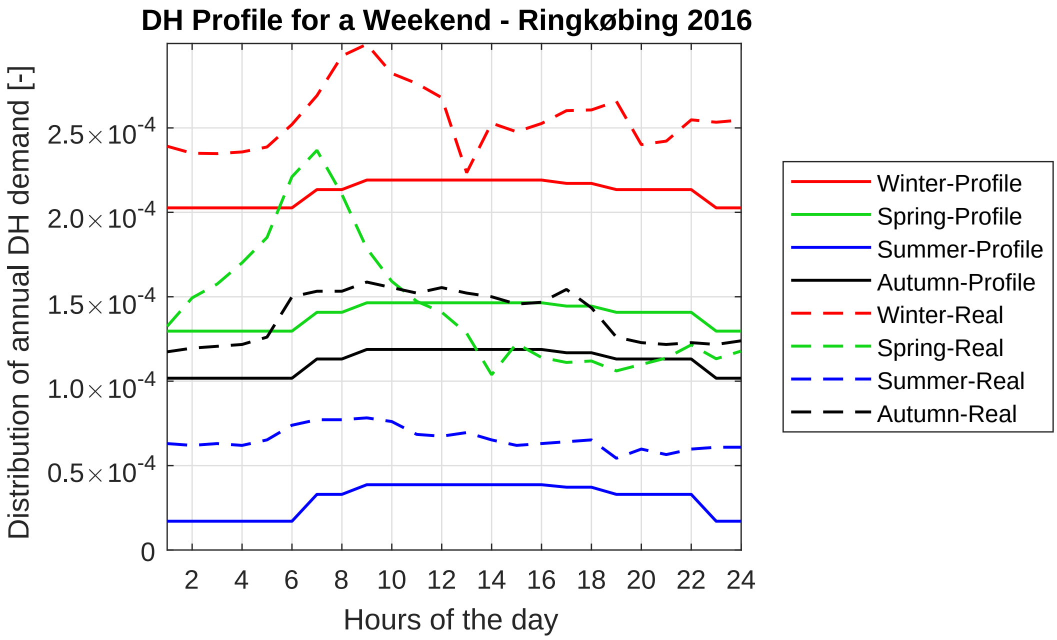

Figure A.4: Comparison of the artificially created hourly district heating profile to the one of Ringkøbing for weekends in in 2016.

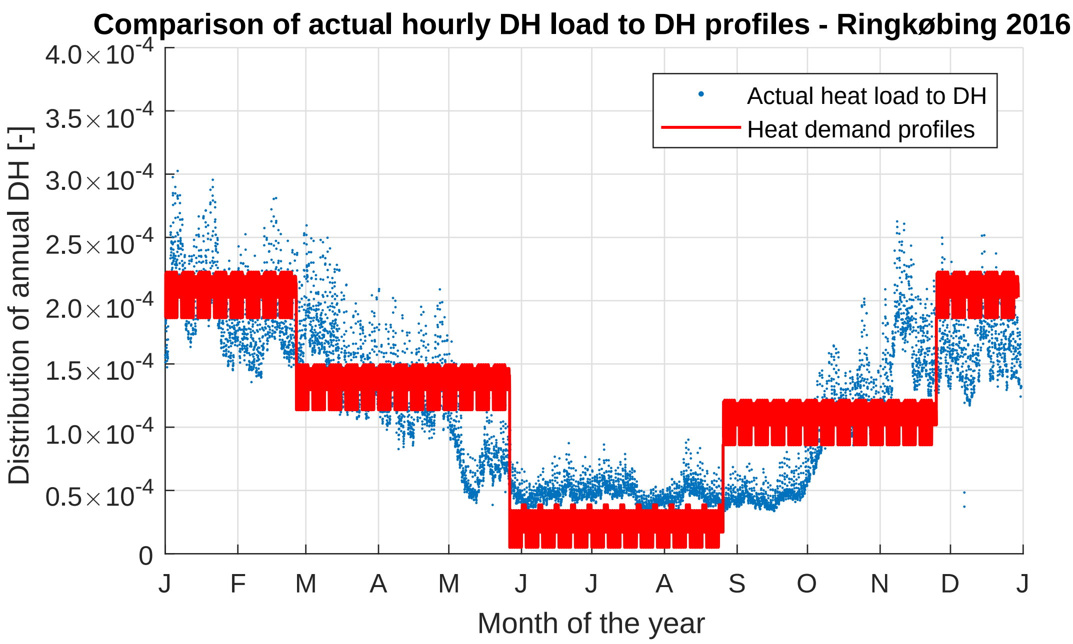

Figure A.5: Comparison of the artificially created hourly district heating profile to the hourly heat load Ringkøbing DH for 2016.

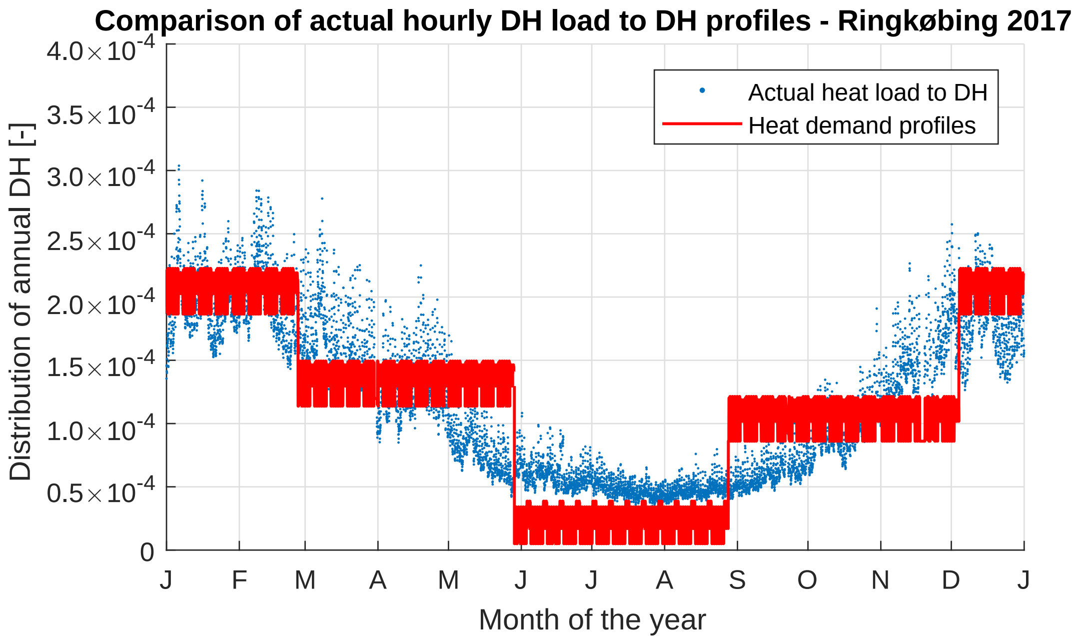

Figure A.6: Comparison of the artificially created hourly district heating profile to the hourly heat load Ringkøbing DH for 2017.

A.6 Sensitivity analysis excess heat potential

In the following the results of a sensitivity analysis for the utilisation potential of excess heat in district heating areas is shown. For illustration of the sensitivity measures, first Figure A.7 is presented. In this figure the buildings supplied by district heating are depicted by green points, other buildings located within district heating area are depicted by red points, while the buildings located outside of district heating areas (black points) were not considered as candidates for connection to district heating in this analysis.

In each of the figure, the district heating demand which can be supplied by industrial excess heat is presented alongside the district heating demand which could be supplied by industrial excess heat but is further away than the cut-off distances. The left half of Figures A.8 to A.11, named *Buildings supplied by DH*, includes only buildings currently supplied by district heating. The right half, named *All buildings within DH areas*, also includes the buildings which are currently not supplied by district heating.

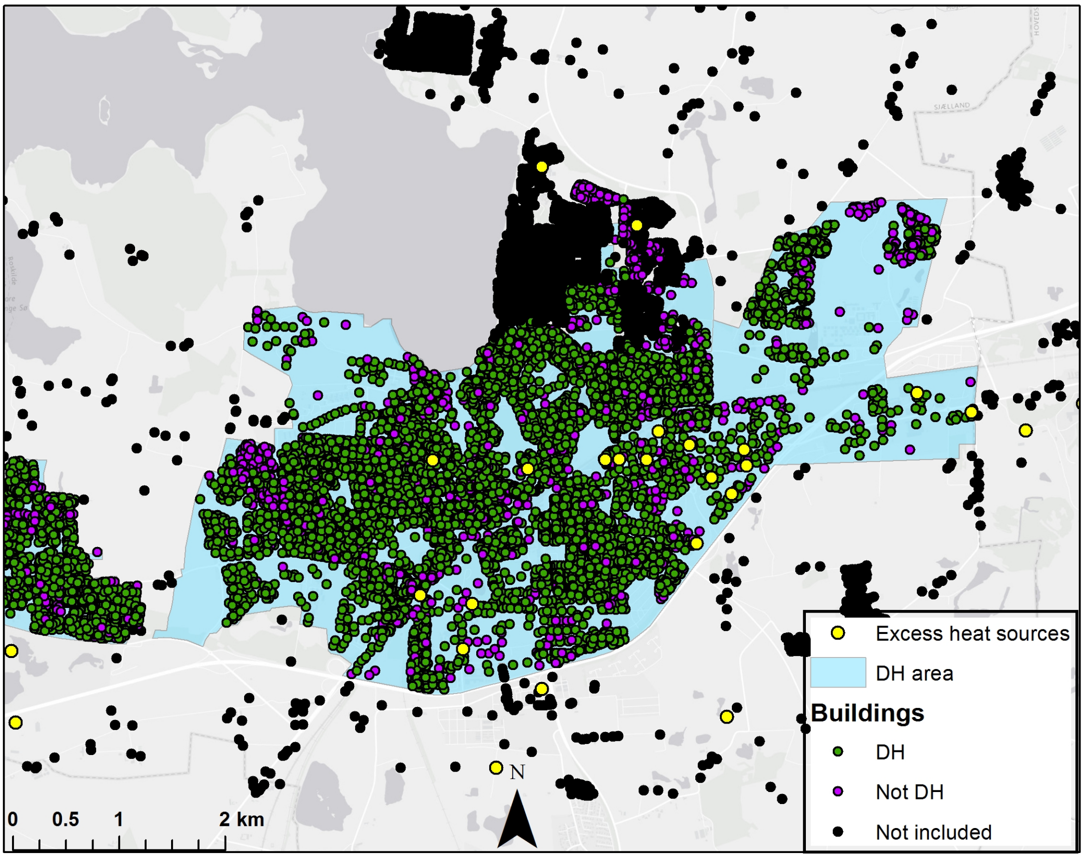

Figure A.7: DH area, EH sources and buildings within and outside of the DH area in the vicinity of the city of Roskilde.

The sensitivity actions are presented in the following four figures:

Figure A.8 presents the heating demand which can be supplied by industrial excess heat if the excess heat sources and district heating grid are kept constant, while the heating demand is decreased by 30 % and 50 %.

Figure A.9 presents the effect of energy efficiency improvements in industries on the utilisation of industrial excess heat for district heating.

Figure A.10 shows the effect of increased energy efficiency of district heating grids by 5 percent points on the district heating demand which can be supplied by industrial excess heat.

Figure A.11 presents the combined effect of energy efficiency improvements in industries and district heating grids on the utilisation of industrial excess heat for district heating.

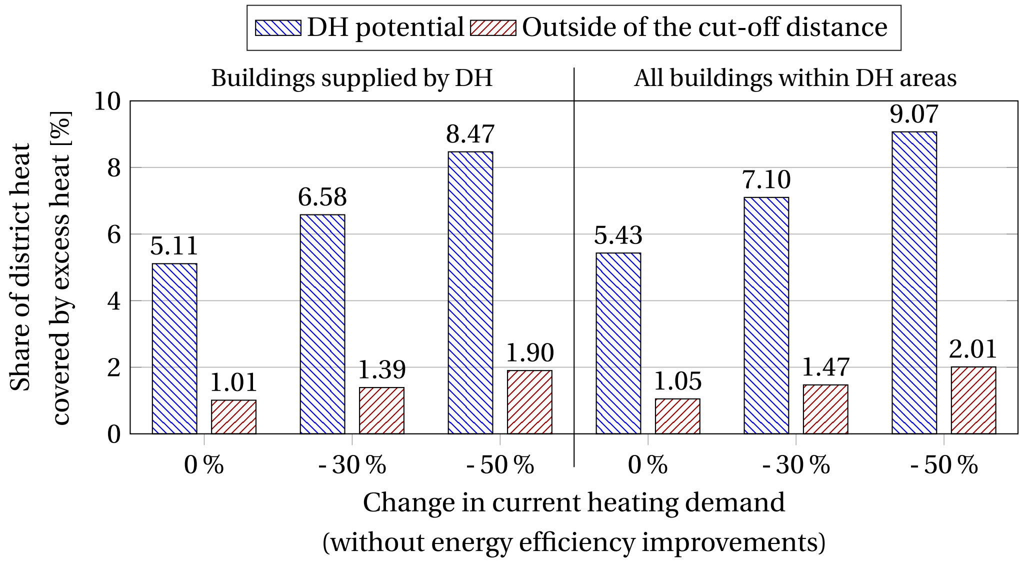

Figure A.8: Potential for supplying DH demand by industrial excess heat for different heating demands.

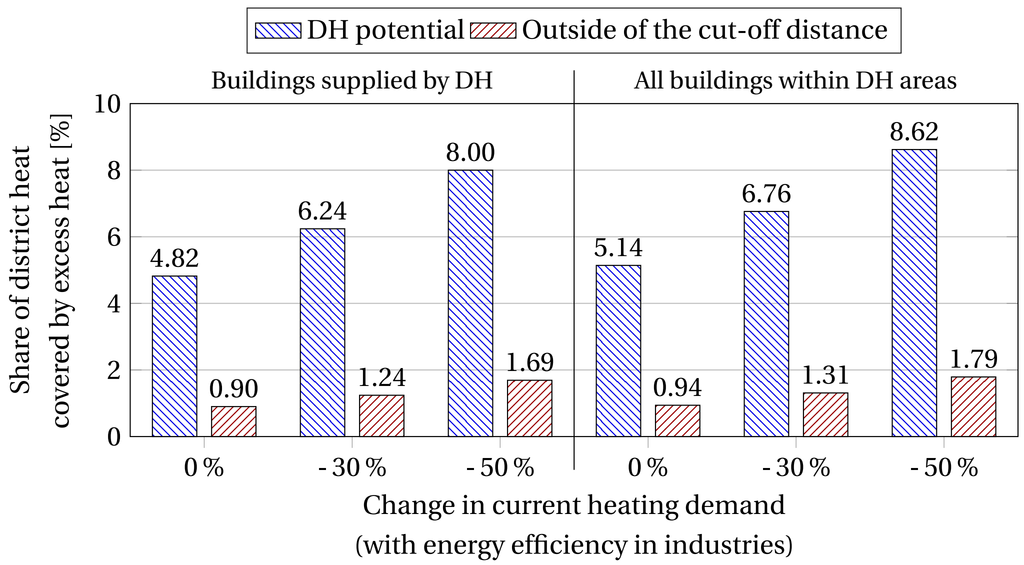

Figure A.9: Potential for supplying DH demand by industrial excess heat for different heating demands and excess heat amounts.

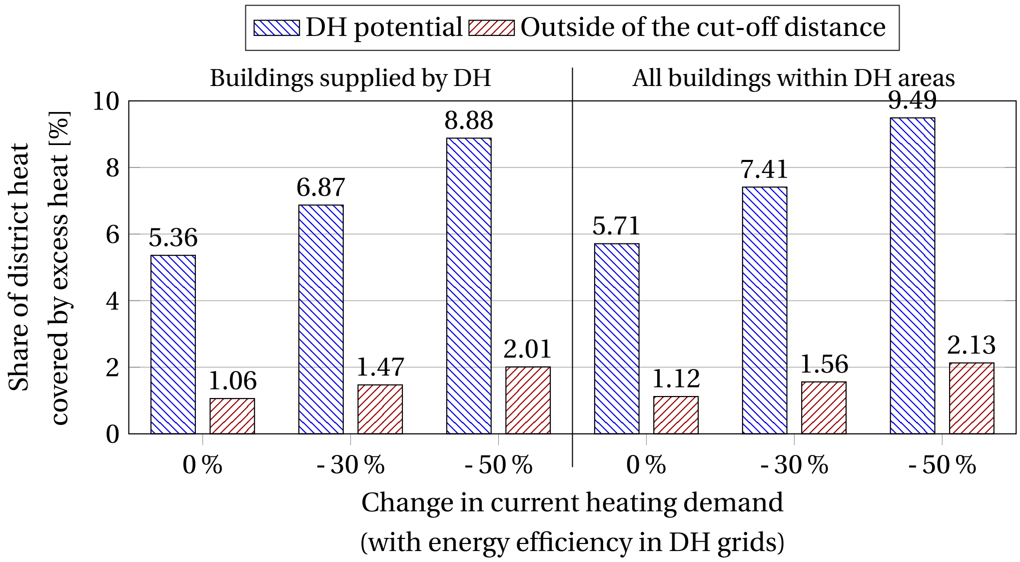

Figure A.10: Potential for supplying DH demand by industrial excess heat for different heating demands and efficiencies of DH grids.

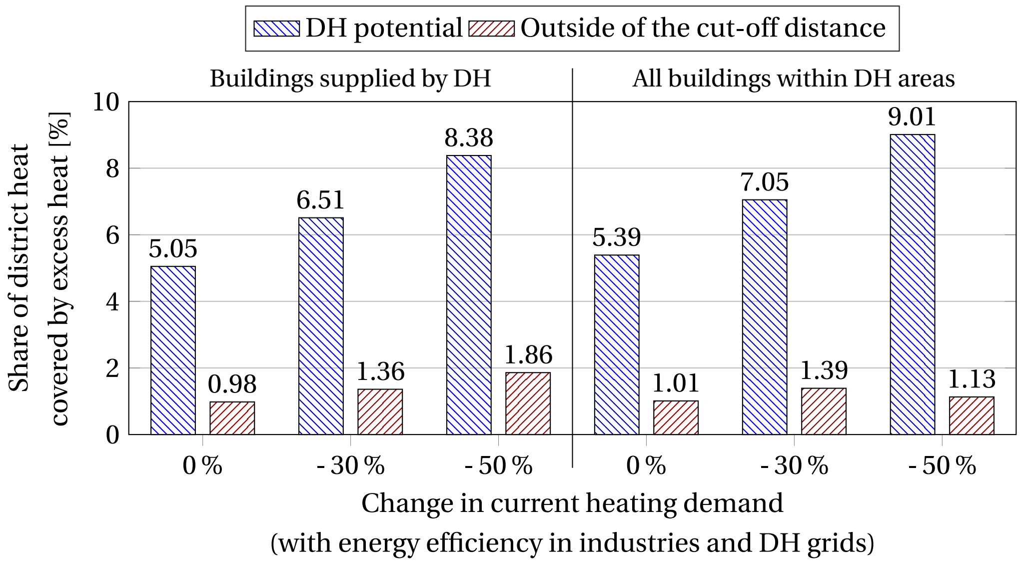

Figure A.11: Potential for supplying DH demand by industrial excess heat for different heating demands, excess heat amounts and efficiencies of DH grids.

B Dairy Analysis

B.1 Dairy composition

Table B.1: Composition of the diary products for the different states based on [274].

	State [-]	Protein [kg/kg]	Fat [kg/kg]	Carbonhydrate [kg/kg]	Ash [kg/kg]	Water [kg/kg]
Raw Milk	M1	0.035	0.035	0.049	0.007	0.874
Skim Milk	M3	0.035	0.001	0.051	0.008	0.905
Cream	C1	0.035	0.290	0.034	0.000	0.641
Mixture	M9	0.049	0.003	0.087	0.011	0.850
Concentrate I	E6	0.128	0.007	0.187	0.028	0.650
Concentrate II	E8	0.153	0.009	0.224	0.034	0.580
Concentrate III	E9	0.172	0.010	0.251	0.038	0.530
Concentrate IV	E10	0.194	0.011	0.283	0.043	0.470
Milk Powder I	P3	0.347	0.019	0.507	0.077	0.050
Milk Powder II	P4	0.356	0.020	0.520	0.079	0.025

B.2 Thermodynamic state points

Table B.2: Thermodynamic state points for the cold utility section (CU).

State [-]	$\dot{m}$ [kg/s]	T [C]	p [bar]	h [kJ/kg]	e [kJ/kg]
RM1	1.3	-4.5	3.5	1459.0	172.9
RM2	1.3	108.1	12.2	1697.0	364.7
RM3	1.3	31.5	12.2	1487.0	332.7
RM4	1.3	31.5	12.2	348.6	271.3
RM5	1.3	30.5	12.2	344.0	271.1
RM6	1.3	-5.5	3.5	344.0	258.3
RM7	1.3	-5.5	3.5	1456.0	173.1
AA1	172.9	15.0	1.0	31.3	0.0
AA2	172.9	25.0	1.0	41.5	0.2
IW1	33.0	9.3	1.0	34.4	0.2
IW2	33.0	-2.5	1.0	-9.1	2.0

Table B.3: Thermodynamic state points for the milk treatment section (MT).

State [-]	$\dot{m}$ [kg/s]	T [C]	p [bar]	cp [kJ kg K]	e [kJ/kg]
M1	11.9	7.0	1.0	3.87	0.4
M2	11.9	50.0	1.0	3.89	7.7
M3	10.7	50.0	1.0	3.96	7.8
M4	10.7	70.0	1.0	3.97	18.5
M5	10.7	75.0	1.0	3.97	21.8
M6	10.7	55.0	1.0	3.96	10.1
M7	10.7	8.0	1.0	3.94	0.3
M8	10.7	5.0	1.0	3.94	0.7
M9	11.7	5.0	1.0	3.80	0.7
M10	11.7	80.0	1.0	3.84	24.5
M11	11.7	85.0	1.0	3.85	28.2
M12	11.7	10.1	1.0	3.80	0.2
M13	11.7	5.0	1.0	3.80	0.7
C1	1.2	50.0	1.0	3.31	6.5
C2	1.2	77.0	1.0	3.33	19.5
C3	1.2	85.0	1.0	3.33	24.5
C4	1.2	58.1	1.0	3.31	9.7
C5	1.2	23.0	1.0	3.29	0.4
C6	1.2	5.0	1.0	3.28	0.6

Table B.4: Thermodynamic state points for the evaporation section (EV).

State [-]	$\dot{m}$ [kg/s]	T [C]	p [bar]	h [kJ/kg]	e [kJ/kg]
E1	11.7	25.0	1.0	95.2	0.6
E2	11.7	74.9	1.0	287.5	20.9
E3	11.7	85.0	1.0	326.8	28.2
E4	11.5	75.0	0.4	287.8	21.1
E5	11.5	75.0	0.4	287.8	21.1
E6	5.0	75.0	0.4	251.8	18.5
E7	5.0	67.0	0.3	224.5	14.1
E8	4.3	67.0	0.3	214.8	13.5
E9	3.8	56.0	0.2	172.3	9.0
E10	3.4	52.0	0.1	152.2	6.4
VE1	6.5	75.0	0.4	2635.0	422.9
VE2	6.5	98.5	0.5	2679.0	459.0
VE3	6.2	98.5	0.5	2679.0	459.0
VE4	0.3	98.5	0.5	2679.0	459.0
VE5	0.3	80.0	0.5	334.9	26.7
VE6	6.2	80.0	0.5	334.9	26.7
VE7	0.7	67.0	0.3	2621.0	375.3
VE8	0.5	58.0	0.2	2605.0	318.9
VE9	0.4	52.0	0.1	2595.0	279.6
VE10	0.3	52.0	0.1	2595.0	279.6
VE11	0.6	127.3	0.5	2736.0	469.3
VE12	0.6	72.0	0.3	301.4	20.8
VE13	0.7	67.0	0.3	1291.0	172.0
VE14	0.5	58.0	0.2	507.6	46.5
VE15	0.2	52.0	0.1	2595.0	279.6
VE16	0.2	52.0	0.1	217.7	9.1
VE17	0.4	239.0	25.0	2848.0	1021.0
VE18	8.5	81.7	0.5	422.3	43.1
VE19	8.5	38.4	0.1	160.9	3.7

Table B.5: Thermodynamic state points for the spray drying section (SD).

State [-]	$\dot{m}$ [kg/s]	T [C]	p [bar]	X [kg/kg]	h [kJ/kg]	e [kJ/kg]
P1	3.4	52.0	1.0	-	152.2	6.4
P2	3.4	75.0	1.0	-	221.0	16.2
P3	1.8	81.0	1.0	-	155.4	12.6
P4	1.8	40.0	1.0	-	76.5	2.0
P5	0.1	40.0	1.0	-	76.5	2.0
A1	64.4	15.0	1.0	0.00643	31.3	0.0
A2	8.1	15.0	1.0	0.00643	31.3	0.0
A3	56.3	15.0	1.0	0.00643	31.3	0.0
A4	56.3	23.3	1.0	0.00643	39.8	0.1
A5	56.3	210.0	1.0	0.00643	231.2	47.5
A6	55.7	210.0	1.0	0.00643	231.2	47.5
A7	0.6	210.0	1.0	0.00643	231.2	47.5
A8	3.1	55.0	1.0	0.00643	72.0	2.6
A9	2.5	15.0	1.0	0.00643	31.3	0.0
A10	5.6	15.0	1.0	0.00643	31.3	0.0
A11	5.6	8.0	1.0	0.00643	24.2	0.1
A12	57.3	78.1	1.0	0.03435	169.4	8.4
A13	8.7	38.4	1.0	0.00748	57.8	0.8
A14	66.0	73.0	1.0	0.02888	149.6	6.6
A15	66.0	73.0	1.0	0.02888	149.6	6.6

Table B.6: Thermodynamic state points for the hot utility section (HU).

State [-]	$\dot{m}$ [kg/s]	T [C]	p [bar]	h [kJ/kg]	e [kJ/kg]
B1	8.6	15.0	1.0	31.3	0.0
B2	8.6	204.4	1.0	225.4	45.1
B3	8.9	1325.0	1.0	1913.0	1129.0
B4	0.3	15.0	1.0	52530.0	51979.0
B5	8.9	224.4	1.0	457.1	110.0
B6	8.9	63.4	1.0	269.3	53.4
HU1	6.7	214.4	25.0	917.9	209.3
HU2	6.7	239.0	25.0	2848.0	1021.0

C Process integration and utility optimisation

C.1 Heat exchanger networks

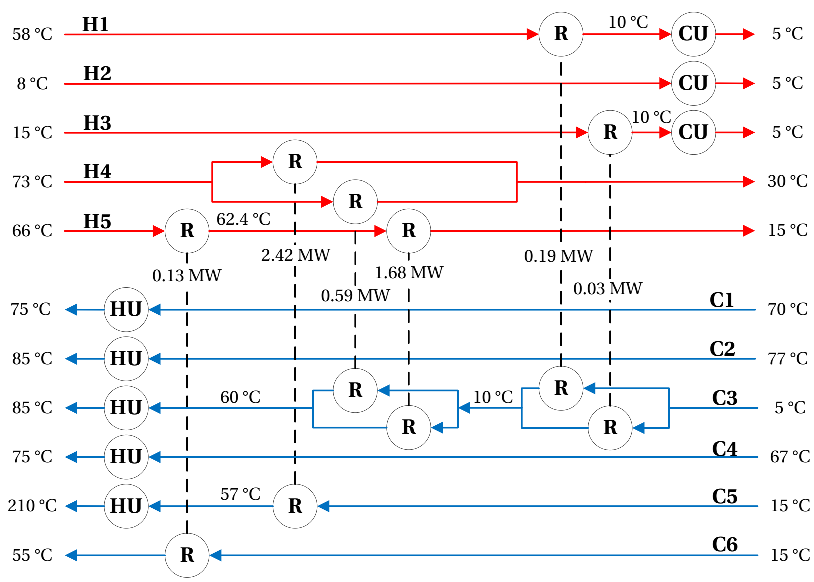

Figure C.1: Heat exchanger network found with the LP Transshipment model for the simplified dairy factory.

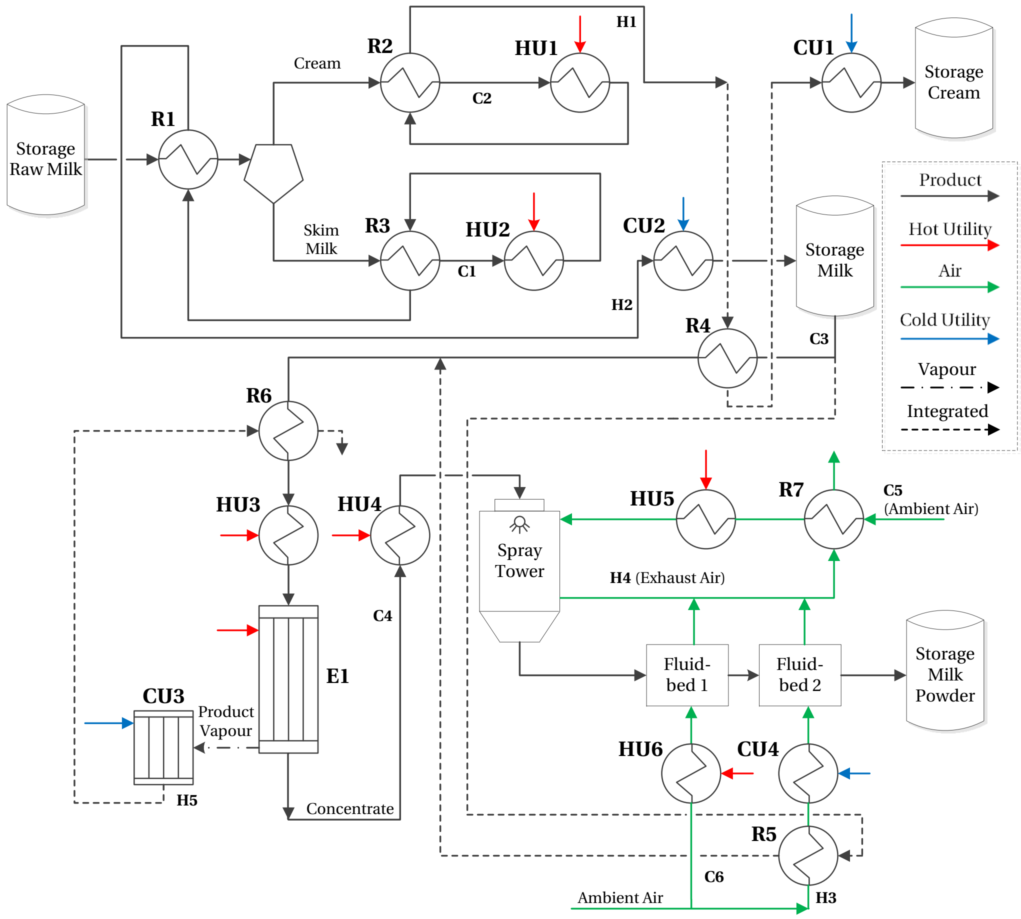

Figure C.2: Heat exchanger network found by simultaneous optimisation of cost and matches integrated into the dairy factory.

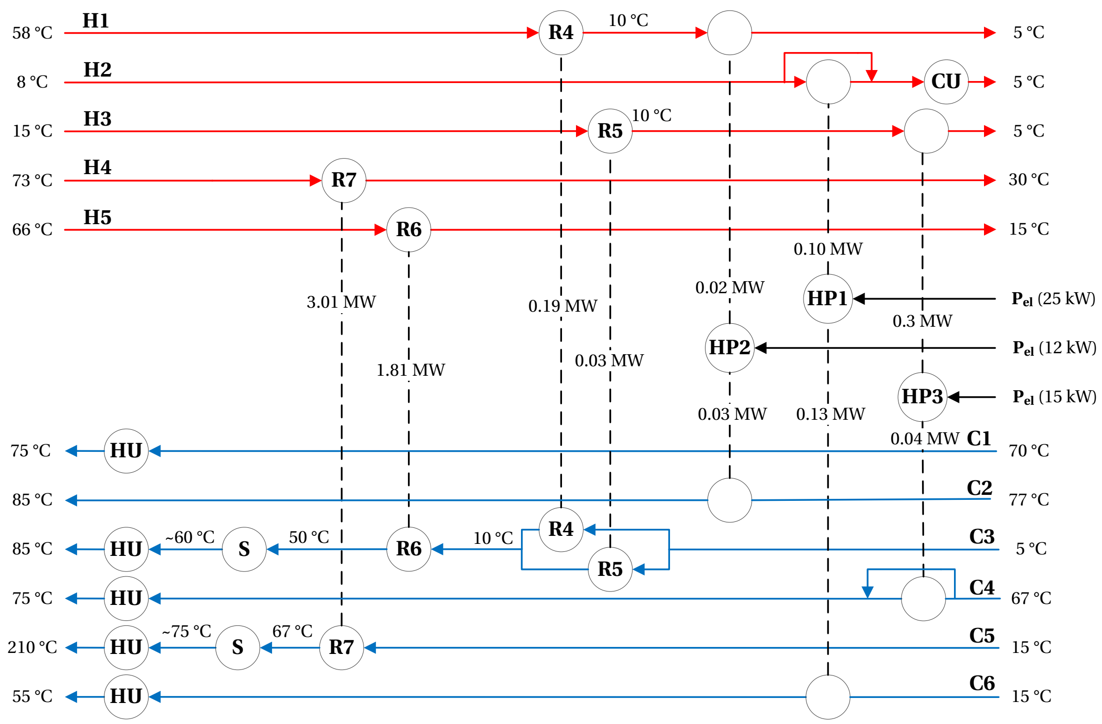

Figure C.3: Final configuration of the heat exchanger network with heat pumps and solar thermal energy.

C.2 Solar uncertainty and sensitivity

C.2.1 Linear regression

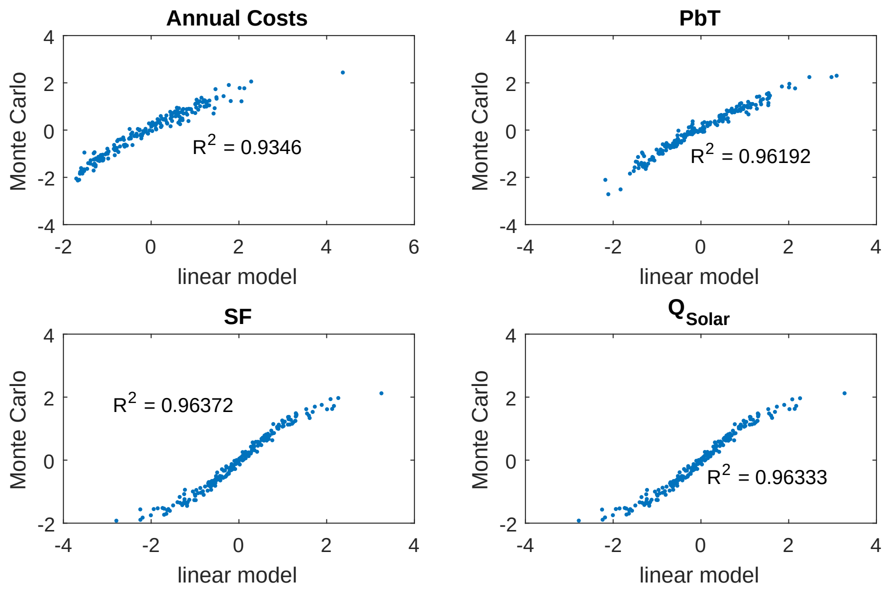

Figure C.4: Linearisation of the original model for HU3 using 200 samples.

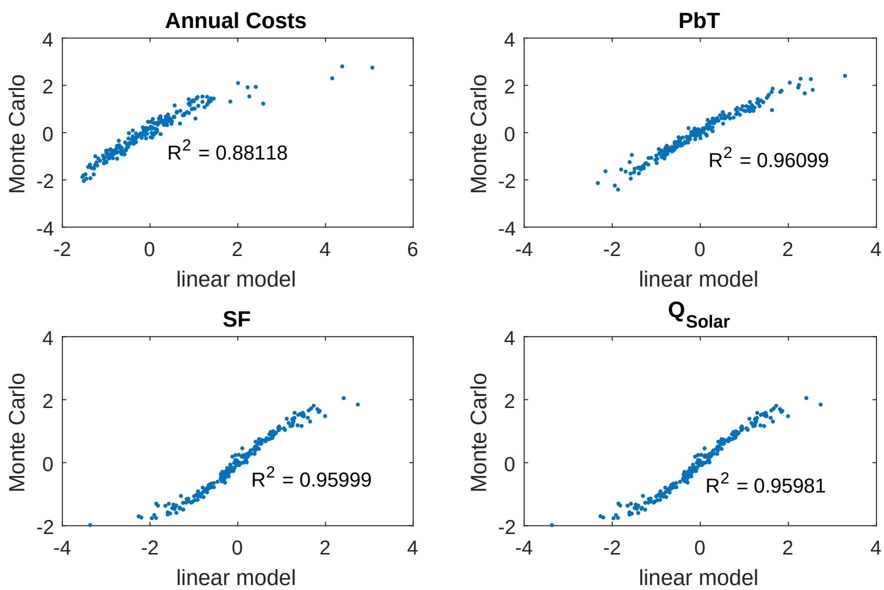

Figure C.5: Linearisation of the original model for HU5 using 200 samples.

C.2.2 Morris Screening

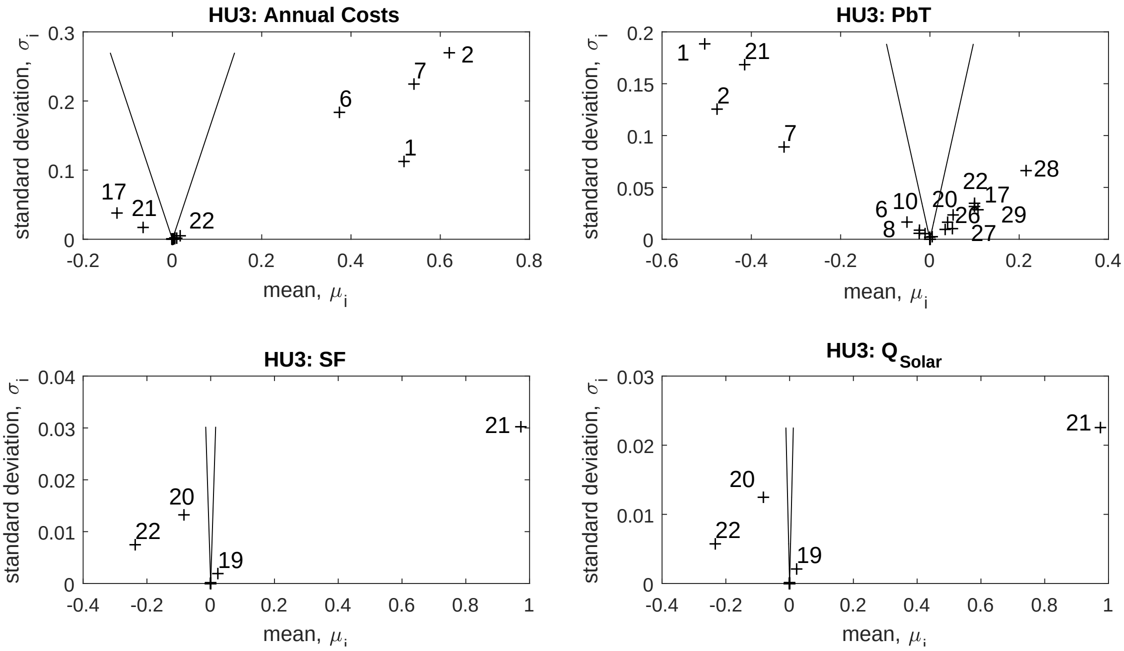

Figure C.6: Results of the morris screening, showing the mean against teh standard deviations for the model input parameters.

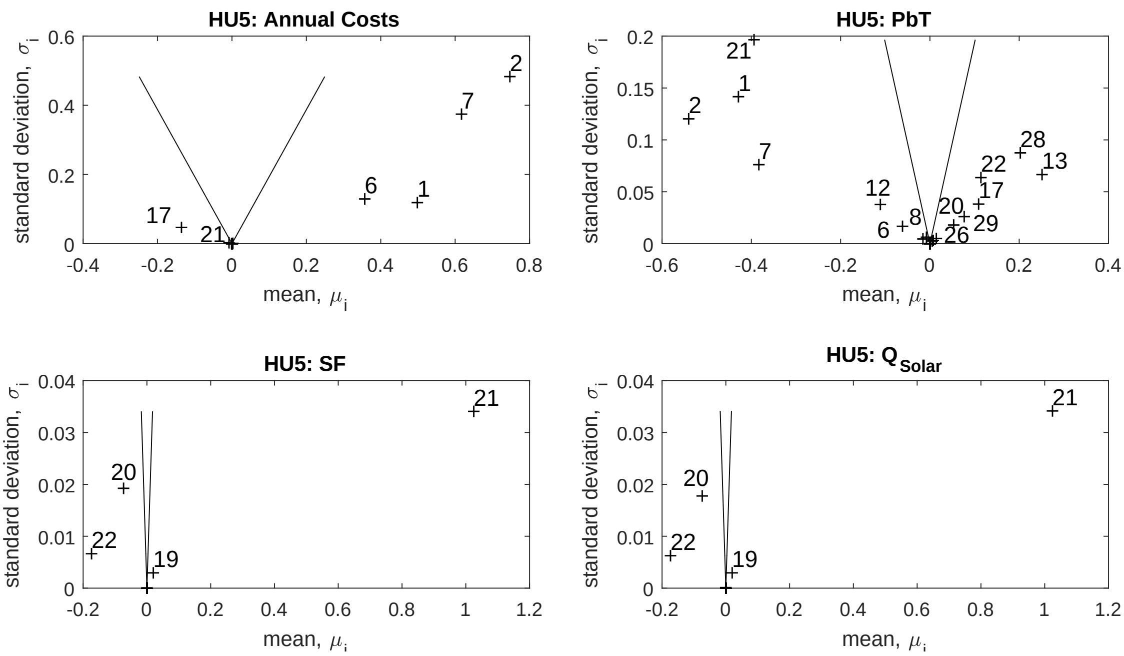

Figure C.7: Results of the morris screening, showing the mean against teh standard deviations for the model input parameters.

D Literature review barrier

D.1 Overview of taxonomies

Blumstein et al. [342] presented a fist classification of barriers to energy saving projects. The six categories were based on different social and institutional barriers. These barriers include

(i) Misplaced incentives (landlord/ tenant scenario),
(ii) Lack of information or misinformation (unawareness of measure),
(iii) Regulation (measures conflict with standards) ,
(iv) Market structure (measures are not on market),
(v) Financing (access to capital/ market failure) and
(vi) Custom (e.g. measure requires some alteration in the habits of the consumer).

Reddy [282] divided barriers into the organisation or institution they are related to. This leads to a classification which differentiates amongst,

(i) Consumer,
(ii) Equipment manufacturer,
(iii) Utility,
(iv) Financial institution and
(v) Government

Painuly and Reddy [343] analysed the barriers for reducing electricity use on the supply and demand side. The barriers are divided, as summarised by Cagno et al. [313], into

(i) Technical,
(ii) Institutional,
(iii) Financial,

(iv) Managerial,

(v) Costs and

(vi) Information.

Weber [322] suggested in a viewpoint, that barriers should be generally classified into

(i) Institutional,

(ii) Market (divided into barriers and failures),

(iii) Organisational and

(iv) Behavioural.

This suggestions was picked up by several authors and is used as a basis in the taxonomy of Sorrell et al. [14].

Sorrell et al. [14] developed oen of the most relevant classifications, which is described in detail in Section 9.3.1. The overall classification is similar to the one proposed by Weber [322], namely

(i) Economic (Market and non-market failure),

(ii) Behavioural and

(iii) Organisation theory.

Sathaye et al. [344], as part of the Working Group III of the Intergovernmental Panel on Climate Change (IPCC), conducted a review of barriers to the implementation of GHG emission mitigation opportunities. Their detailed classification considers

(i) Technological innovation,

(ii) Prices,

(iii) Financing,

(iv) Trade and environment,

(v) Institutional frameworks,

(vi) Information provision and

(vii) Social, cultural and behavioural norms and aspirations.

De Almeida et al. [345] considered in more detail the barriers to energy-efficient motor technologies, but also included general ones form a very practical stand point. The barriers used are

(i) Awareness of options,

(ii) Technical options,

(iii) Economic barriers,

(iv) Internal conflicts and

(v) Market structure.

Reddy [346] developed another taxonomy named *M3T*, which classifies the barriers as micro, meso and macro. Here, micro-barriers are the one to occur on the lowest level, i.e. barriers which are unique to a particular project. Meso-barriers relate to the organisations connected to a given project. These meso-barriers are to be common to a wide range of projects and are a result of e.g. an inefficient organisation or a lack of human resources. Finally, macro-barriers, which occur on the highest level, refer to state, market and civil society. These barriers are usually not solvable by a specific project or organisation.

The taxonomy developed by Cagno et al. [313] is based on the lacks of other taxonomies determined from the literature, in particular form Sorrell et al. [14]. It first identified missing elements in the taxonomy from Sorrell et al. [14]. These elements include amongst others the following barriers. The distortion in energy resource prices is an aspect not included, as only the prices paid by the consumer are considered without the external cost of energy. The low diffusion of technologies should also be further included. Further it has to be noted that not all technologies, as well as their management, are fully available.
Secondly, it is proposed to disaggregate the barriers according to the theoretical models, which would allow to collect and investigate different approaches. The barriers heterogeneity, imperfect information, incomplete markets and bounded rationality from [342] and Sorrell et al. [14] are disaggregated.
As the third element of the developed taxonomy, implicit interactions of barriers are introduced. As there are possible interactions between barriers or sets of barriers, several problems might arise when developing e.g. policies. Some implicit interaction from the Sorrell taxonomy is for example the principal-agent relationship, which represents two separate barriers. Namely a lack of control over operators and an opportunistic agent behaviour. Both actions at the same time could results in higher rates of return.
Based on these elements the taxonomy is developed to include a minimum amount of terms, while still being able to analyse possible interactions. The origin of the barriers are further classified into external and interal, with respect to the firm. Internal barriers are found within the firm. In table D.1 the barriers from Cagno et al. [313] are summarised and grouped according to being internal or external and by actor or area.

D.2 Overview of the studies on barriers for energy efficiency

Table D.1: Taxonomy proposed by Cagno et al. [313] with a distinction of the origin (internal and external) of the barrier (Table adopted from Cagno et al. [313]).

Origin	Actor/ Area	Barrier
External	Market	Energy prices distortion
		Low diffusion of technologies
		Low diffusion of information
		Market risks
		Difficulty in Gathering External Skills
	Government/politics	Lack of proper regulation
		Distortion in fiscal policies
	Technology/	Lack of interest in energy efficiency
	services suppliers	Technology Suppliers not updated
		Scarce communication skills
	Designers and	Technical Characteristics not adequate
	manufacturers	High initial costs
	Energy suppliers	Scarce communication skills
		Distortion in energy policies
		Lack of interest in energy efficiency
	Capital suppliers	Cost for investing capital availability
		Difficulty in identifying the quality of the investments
Internal	Economic	Low capital availability
		Hidden costs
		Intervention-related risks
	Behavioral	Lack of interest in energy-efficiency interventions
		Other priorities
		Inertia
		Imperfect evaluation criteria
		Lack of sharing the objectives
	Organisational	Low status of energy efficiency
		Divergent interests Complex decision chain
		Lack of time Lack of internal control
	Barriers related to	Identifying the inefficiencies
	competences Awareness	Implementing the interventions
		Lack of awareness or Ignorance

Table D.2: Overview of the main publications using empirical data about barriers to energy efficiency in the industry.

Study	Region	Industry Type	Type of Study	Identified Main Barriers
[180]	Sweden	Excess heat	Semi- structured interviews (8); Exploratory study;	Lack of heat user, lack of other technologies over EH in DH areas, risk of closing the production, solution not profitable
[347]	Sweden	Iron and steel	Mixed method approach; Questionnaire (46); Follow up interviews (10);	Technical risk, Limited access to capital, other priorities for investments and lack of time;
[348]	Italy	SME industry	Multiple case studies (15); empirical and exploratory research;	Other priorities, implementing the interventions, lack of time, low capital availability
[349]	Italy	Manufacturing industry	Multiple case studies (61); phone interviews;	Economic, behavioural and lack of awareness
[317]	Netherlands	Chemical	Multiple case study approach (17); survey and interviews;	Future energy prices, economic trend and commitment at an institutional level;
[350]	Netherlands	Industry	Survey (135);	Other investments more important, technology only relevant after renovation, energy costs are not important
[351]	Germany	Industry	Survey (542); Multivariate analyses;	Investment costs too high, other investments more important, measure not profitable, energy price uncertainty;
[138]	Germany	Industry	Case studies; Workshop;	Structural barriers (location of EH and heat user), costs for identifying measures too high compared to possible savings, technical risk and core business

Table D.2 continued:

Study	Region	Industry Type	Type of Study	Identified Main Barriers
[352]	Sweden	Non-energy intensive manufacturing	Case studies; Semi structured interviews;	Cost of production disruption/ hassle/ inconvenience, lack of time, other priorities, cost of obtaining information
[315]	Sweden	Foundries	Case study using questionnaire;	Access to capital, technical risks such as risk of production disruptions, lack of budget funding
[353]	Greece	Manufacturing industry	Model using cross section data; Empirical analysis; Questionnaires in interviews (779);	Lack of access to capital, slow rate of return, cost of implementation of EEM, other investment opportunities
[314]	UK	Mechanical and Breweries	Case studies; Questionnaires;	Access to capital, hidden costs (for smaller breweries), imperfect information
[354]	7 EU conturies	Foundries	Multiple case studies (65);	Driving forces: rising prices, cost reductions from lowered energy use
[355]	Sweden	Manufacturing SME	Questionnaire (47);	Lack of time or other barriers, other priorities for capital investments, access to capital
[325]	Sweden	Pulp and Paper	Research case studies with questionnaires;	Technical risks and costs of production disruptions/ hassle/ inconvenience, technology is inappropriate at the factory
[356]	Italy (North)	Manufacturing SME	Semi structured interviews;	Access to capital, Scarce information regarding EE opportunities and winning solutions, poor information for the EE decisions, lack of internal technical skills

Table D.2 continued:

Study	Region	Industry Type	Type of Study	Identified Main Barriers
[320]	Italy	Manufacturing SME	Semi Structured interviews (222);	Economic barriers, information related, behavioural barriers
[326]	EU	Foundries	Multiple case studies; Semi-structured interviews and questionnaires(123);	Lack of budget funding, other priorities for capital investments, lack of time or other priorities, department or workers not accountable for energy costs
[357]	Italy	Primary metals	Multiple case studies; Semi-structured interviews and questionnaires (20);	Information issues on energy contracts, lack of interest in energy-efficiency interventions, hidden costs, investment costs
[327]	Belgium	Ceramic, cement and lime	Multiple case studies (16); Loosely structured interviews; Qualitative methodology;	Other (non-energy-related) investments receive prior financing, Low demand risk: efficiency investments entail fixed costs that may be cost-inefficient when there is overcapacity during economic downturns, technical feasibility not studied before
[179]	UK	Excess heat	Experience; Views of stakeholders;	Infrastructure, financial support, capital cost, location, suitable end users, communications and awareness.
[316]	Denmark	SME industry	Survey (849)	Too long PbT of the investment, rate of return too low, prioritisation of other investments, limited access to capital, lack of information

I may not have gone where I intended to go,
but I think I have ended up where I needed to be.

— Douglas Adams, The Long Dark Tea-Time of the Soul

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