NEFI
NEW ENERGY FOR INDUSTRY

klima+ energie fonds

13.10.22 - 14.10.22

CONFERENCE OF THE INNOVATION NETWORK

NEW ENERGY FOR INDUSTRY 2022

LINZ, AUSTRIA

#NEFI2022

NEFI-New Energy for Industry is part of the „Vorzeigeregion Energie", funded by the Austrian Climate and Energy Fund, and pursues the approach of decarbonizing the industrial energy system with key technologies „Made in Austria". The NEFI - Innovation Network has formed around a consortium of AIT Austrian Institute of Technology, Montanuniversität Leoben, OÖ Energiesparverband and the Upper Austrian business development agency Business Upper Austria and bundles the diverse experience in the field of energy research and implementation of projects. Significant support also comes from the two federal states of Upper Austria and Styria. www.nefi.at

AIT AUSTRIAN INSTITUTE OF TECHNOLOGY · MONTAN UNIVERSITÄT LEOBEN · business upper austria · OÖ ENERGIESPARVERBAND · VORZEIGEREGION ENERGIE · ober österreich · Das Land Steiermark

Conference Proceedings

New Energy for Industry 2022

2nd Conference of the Innovation Network

October 13-14, 2022 in Linz, Austria

The NEFI innovation network of science, technology providers and companies demonstrates a pathway towards the decarbonisation of industry

Decarbonisation
of industrial energy systems
100 % renewable energy supply at selected locations

Added value “Made in Austria”
through export and technology development

Contribution
to secure industrial and economic location Austria by user involvement

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FOREWORD NEFI INNOVATION NETWORK

Today, Austrian industry as a whole consumes approximately 110 TWh each year, equating to around 27% of gross domestic product. While carbon emissions are decreasing in the building sector and climate-friendly solutions are gradually impacting transportation, this downward trend has not yet started in industry. The innovation network "NEFI - New Energy for Industry", funded by the Austrian Climate and Energy Fund together with the federal states of Styria and Upper Austria, demonstrates feasible solutions for achieving climate neutrality in the industrial sector. NEFI shows how climate action contributes to Austria's long-term security as an industrial location, and how comprehensive technologies "Made in Austria" can be implemented globally. NEFI covers a wide range of technological and systemic action fields addressing climate neutrality:

- New energy-efficient process technologies
- Storage systems
- Industrial demand-side management solutions

NEFI also addresses methods for energy exchange between industrial sites and the public energy grid, future business models and policy recommendations, and industry-compatible solutions for tomorrow's energy infrastructure. Interaction between the different fields of action leads to (cross-energy) system solutions which are also explored in the NEFI innovation network. The network was established by the AIT - Austrian Institute of Technology, Montanuniversität Leoben, OÖ Energiesparverband, and Business Upper Austria. It brings together broad-ranging expertise in energy research and project implementation, forming a consortium consisting of over 100 companies, 14 research partners, and 5 institutional partners.

The challenges we currently face should be viewed as an opportunity to actively define tomorrow's industrial energy system. Achieving carbon neutrality in a timely manner depends to a large extent on the infrastructure and energy industry decisions that are taken today. Consequently, representatives from science, research, business and industry associations, and politics are encouraged to contribute to the successful development of the European energy industry and society, as presented and intensively discussed during the 2nd NEFI conference. During the conference, which was attended by over 200 participants, around 35 speakers debated aspects of the industrial transition to climate neutrality, the significance of research and innovation and the necessary framework conditions.

WOLFGANG HRIBERNIK

NEFI Network Coordinator

Head of Center for Energy, AIT Austrian Institute of Technology

THOMAS KIENBERGER

Head of NEFI_Lab

Head of Chair for Energy Network Technology at Montanuniversitaet Leoben

CHRISTIANE EGGER

Member Cluster Steering Committee

Deputy Manager OÖ Energiesparverband, Manager Cleantech-Cluster Energy

DORIAN WESSELY

Member Cluster Steering Committee

Business Upper Austria Manager Cleantech-Cluster Environment

ACKNOWLEDGEMENT NATIONAL RESEARCH FUNDING

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“Industry must get out of the oil and gas business - this is the only way to achieve climate targets and reduce dependence on imports. Through NEFI we are demonstrating and implementing climate-effective research projects in our model regions to ensure that energy intensive industry is on the right path.”

Theresia Vogel
Managing Director of the Climate and Energy Fund, Austria
www.klimafonds.gv.at

© Teresa Rothwangl

“In the context of climate change and rapidly rising energy prices, the green transformation is more important than ever. In this context, I am convinced that science and research are critical to resolving current challenges and encouraging the energy transition. With its forward-thinking work, the NEFI consortium contributes significantly to the decarbonization of domestic industry. The NEFI conference in Linz provided an excellent opportunity for an important expert exchange and served to strengthen our cooperation across federal states.”

Barbara Eibinger-Miedl
Regional Minister for Economy, Tourism, Regions,
Science and Research, Federal State of Styria
www.zukunftsressort.steiermark.at

© Michael Schnabl

“Even without the challenges posed by the current geopolitical situation, we are in the middle of a crucial decade. Central measures of climate protection and in the current energy crisis are all those that address energy efficiency or the reduction of energy consumption and the transformation of our energy system. The main aim is to break the dependency on fossil resources from abroad. Styria is not only a strong research state, Styria also has a long, proud tradition as an industrial state. That is why I am convinced, that we will expand our energy independence and achieve the energy transition together with combined forces! “

Ursula Lackner
Regional Minister for Environment, Climate Protection, Energy, Regional Development and Spatial Planning, Federal State of Styria
www.zukunft.steiermark.at

© Land OÖ

„Stepwise phase-out of fossil fuels and the global changes in the energy and industrial systems through decarbonisation and decentralisation are shaping the future of our economy. With NEFI we are supporting this process. Innovative energy technology companies based in Upper Austria play an important role in this transformation.“

Markus Achleitner
Regional Minister for Economy and Energy,
Federal State of Upper Austria
www.markus-achleitner.at

PROGRAMME

NEW ENERGY FOR INDUSTRY

Day 1
Thursday,
13th October 2022

Overview Day 1

09.00 – 10.00
Check-in and Get-Together

10.00 – 10.50
Opening
The path to climate neutral industry

10.50 – 12.00
Keynotes

12.00
Lunch Break

13.00 - 13.45
Impulse lecture
NEFI's levers of action for climate neutrality

14.00 – 15.15
Parallel Sessions

15.15 – 16.00
Poster Session

16.00 – 17.15
Parallel Sessions

17.15 – 17.30
Summary and conclusion day 1

18.30 - 21.00
Conference dinner and Young Scientist Award Ceremony

09.00 - 10.00
Check-in and Get-Together

10.00 - 10.10
Opening

WOLFGANG HRIBERNIK
NEFI Network Coordinator, Head of Center for Energy, AIT Austrian Institute of Technology GmbH (AIT)

Moderator

CORNELIA ERTL

10.10 - 10.50
The path to climate neutral industry

HENRIETTE SPYRA
Head of Section III 'Innovation and Technology', Federal Ministry for Climate Protection, Energy, Mobility, Innovation and Technology (BMK)

MARKUS ACHLEITNER
Regional Minister for Economy and Energy, Region of Upper Austria

BARBARA EIBINGER-MIEDL
Regional Minister for Economy, Tourism, Regions, Science and Research, Region of Styria

URSULA LACKNER
Regional Minister for Environment, Climate Protection, Energy, Regional Development and Spatial Planning, Region of Styria

ELVIRA LUTTER
Programme Manager, Director of the Net-Zero Industries Mission by Mission Innovation, Austrian Climate and Energy Fund

10.50 – 12.00
Keynotes

Strategy options for the climate protection in the industry

MANFRED FISCHEDICK
Wuppertal Institute for Climate, Environment and Energy

Role of international cooperation to advance industrial decarbonisation

RANA GHONEIM
United Nations Industrial Development Organisation (UNIDO)

Industry and The Green Deal

DOMINIQUE PLANCHON
Programme Officer, European Commission, DG Research & Innovation

12.00 – 13.00 Lunch Break

13.00 - 13.45
Impulse lecture

NEFI's levers of action for climate neutrality

PETER NAGOVNAK
Research Associate, Chair of Energy Network Technology of Montanuniversität Leoben

CHRISTIAN SCHÜTZENHOFER
Senior Expert Advisor, Center for Energy, AIT

13.45 – 14.00
Break and change to the Parallel Sessions

14.00 - 15.15
Parallel Sessions (see page 3)

15.15 - 16.00
Break / Poster Session (see page 4)

16.00 - 17.15
Parallel Sessions (see page 4)

17.15 - 17.30
Summary and conclusion of the first conference day

CHRISTIANE EGGER
Deputy Manager OÖ Energiesparverband, Manager Cleantech-Cluster Energy

18.30 - 21.00
Conference dinner and Young Scientist Award Ceremony
Ars Electronica Skyloft, Ars-Electronica-Straße 1, 4040 Linz

PROGRAMME

NEW ENERGY FOR INDUSTRY

Day 1
Thursday,
13th October 2022

14.00 - 15.15

Session 1
Energy Management and Flexibility Options

An increased use of volatile renewable energy sources in industrial energy systems necessitates integrated and cross-sectoral energy infrastructure planning, as well as optimised flexibility integration. Against this background, the topics of this session include energy management and storage, innovative energy conversion technologies, and demand-side management (DMS) solutions.

Moderator

THOMAS KIENBERGER
Head of Chair of Energy Network Technology, Montanuniversität Leoben

Keynote: Challenges and options for the capacity management of grids through the use of flexible load

ANDREAS ABART
Netz OÖ GmbH

Recycling and second use of green hydrogen from semiconductor industry

MARTIN SAGMEISTER
HyCentA Research GmbH

The role of forecasting energy consumption and demand in the iron and steel industry - by the example of an electric arc furnace

VANESSA ZAWODNIK
Montanuniversität Leoben

Flexibility identification of an industrial production

KARL-WILHELM SCHENZEL
TU Wien, Institute of Energy Systems

14.00 - 15.15

Session 2
Industrial Waste Heat Utilisation

This session focuses on the development of technological and systemic utilisation solutions for industrial energy flows, such as process heat, in order to meet energy demand. Such energy networks not only minimise industrial energy demand for production energy, but also primary energy demand for the overall energy system. The utilisation of industrial waste heat or the adoption of novel heat exchange technologies are two highly beneficial solutions that can be applied, both of which will be explored in this session.

Moderator

VERONIKA WILK
Senior Research Engineer, Center for Energy, AIT

Keynote: Wienerberger decarbonisation programme

JOHANNES RATH
Chief Technology Officer Building Solutions Wienerberger AG

A techno-economic and macro-economic concept study of waste heat utilisation of a cement plant

STEFAN PUSCHNIGG
Energy Institute at JKU Linz

Assessment of the future waste heat potential from electrolysers and its utilisation in district heating

STEFAN REUTER
Center for Energy, AIT

Renewables vs. waste heat? Legal provision on the original energy source

MARIE-THERES HOLZLEITNER
Energy Institute at JKU Linz

14.00 - 15.15

Session 3
Disruptive Technologies for a Decarbonised Energy System

This session addresses technological and systemic utilisation strategies to accelerate the industrial energy transition in order to meet industrial energy demand while reducing process-related CO_2 emissions. Against this background, the topics of this session include options to reduce dependency on natural gas, as well as sustainable technologies to transform Austria's material products industry.

Moderator

CHRISTIANE EGGER
Deputy Manager OÖ Energiesparverband, Manager Cleantech-Cluster Energy

Keynote: H_2 based CO_2 free factory

STEPHAN LAIMINGER
Chef Technologist at INNIO Jenbacher

The Austrian electricity sector's dependence on natural gas and a way out

ALEXANDER KONRAD
TU Graz, Institute of Electricity Economics and Energy Innovation

Tech4green - disruptive technologies for a sustainable transformation in the Austrian material goods production

NADINE BRUNNHUBER
Institut für Industrielle Ökologie

PROGRAMME

NEW ENERGY FOR INDUSTRY

Day 1
Thursday,
13th October 2022

16.00 - 17.15

Session 1
Industrial Process Optimisation

This session focuses on the decarbonisation of industrial processes, such as lowering CO_2 emissions through efficient energy use and the use of novel technologies or processes. Disruptive process technologies, optimisation strategies and alternative process routes will be particular focus of this session.

Moderator

WOLFGANG HRIBERNIK
NEFI Network Coordinator, Head of Center for Energy, AIT

Keynote: New horizons - decarbonisation within the steel industry for a sustainable future

MONIKA HÄUSELMANN
Senior Project Manager
K1-MET GmbH

Ganymed - the development of an industrial load profile generation software

PAUL BINDERBAUER
Montanuniversität Leoben

Sustainable transformation of SMEs in the context of the Green Deal

ANDREAS CHRISTIAN MELTZER
Joanneum Research

Energy optimisation of a bakery

JANA REITER
AEE Intec

16.00 - 17.15

Session 2
New Industrial Processes - Industrial Heat Utilisation

This session covers technological and systemic utilisation solutions for industrial heat networks, such as industrial heat pumps or heat exchange systems, which have been developed to meet industrial thermal demand. The use of industrial heat pumps or the adoption of novel heat exchange technologies are two solutions that can be highly beneficial in reducing not only the energy demand of industrial production, but also the primary energy demand of the whole energy network.

Moderator

GERALD STEINMAURER
Head of Energy Systems at Austria Solar Innovation Center (ASiC), FH OÖ

Ejector technologies for performance increase of industrial heat pumps

GERWIN DREXLER-SCHMID
Center for Energy, AIT

How to enable interregional heat exchange? Review and analysis of best practice examples

NICOLAS MARX
Center for Energy, AIT

Simulation of the district heating network with a computer programme

JICHEN WU
FlexTechnologies

15.15 - 16.00

Poster Session

Energy management and digitalisation bibliometric analysis

GERTA KAPLLANI
Montanuniversität Leoben

Direct CO_2 electroreduction from cement flue gas – options and opportunities

THOMAS MAIREGGER
Rohrdorfer Group

Heat exchange in industrial microgrids

GERALD STEINMAURER
Austria Solar Innovation Center (ASiC), FH OÖ

Next generation thermal energy storage for industry and building sector

THOMAS NOLL
FET - Future Energy Technologies

Comparing the CO_2 emission intensity of the steel industries in the EU and China resulting from top-down and bottom-up approaches

ARNE BURDACK
Forschungszentrum Jülich GmbH

PROGRAMME

NEW ENERGY FOR INDUSTRY

Day 2
Friday,
14th October 2022

Overview Day 2

08.30 - 09.00
Check-in and Get-Together

09.00 - 09.10
Opening

09.15 - 12.00
Parallel Events

12.00 - 13.00
Lunch and conclusion

08.30 - 09.00
Check-in and Get-Together

09.00 - 09.10
Welcome and Opening

THOMAS KIENBERGER
Head of Chair of Energy Network Technology, Montanuniversität Leoben

THERESIA VOGEL
Managing Director, Austrian Climate and Energy Fund

9.15 - 12.00
Workshop 1:
IEA IETS Task 19 Electrification of Industry Workshop

The industrial sector aims to make use of green electricity as a source for energy and feedstock production towards reducing climate impacts. Electrifying industry implies important changes to processes and also influences the entire energy supply chain. This workshop aims to give an overview about the broad topic of industrial electrification, its importance in the decarbonisation innovation system, and its international context: technologies for direct and indirect electrification, country-specific perspectives from the IEA IETS Task 19 participants, energy resource demand from industries, demand for system and infrastructure services.

Language:
English

Moderator

SIMON MOSER
Energy Institute at JKU Linz

Introduction

SIMON MOSER
Energy Institute at JKU Linz

Keynote: The path to climate-neutral industry in 2040 – the key factor is innovation

THERESIA VOGEL
Austrian Climate and Energy Fund

Electrification of industry – categorisation of a broad topic and update on the work done in IEA IETS Task 19

JONATHAN BOTERO MONCADA
TNO and IETS-19 Task Manager

Presentations from IEA IETS 19 participating countries, in randomized order.

- Country perspectives on electrification from Germany, The Netherlands, Sweden and Austria
- Technology and system insights from R&D projects
- Direct electrification, heat pumps and hydrogen
- Efficiency first and exergy-orientation, whole-industry hydrogen demand
- Implications on generation, transmission, storage and imports

Audience quick surveys & direct Q&A with the speakers

09.30 - 12.00
Workshop 2:
NEFI Technology Talk – Decarbonisation of heating and cooling supply with geothermal energy and industrial waste heat

The global innovation landscape provides an excellent basis for the development of novel solutions to achieve the targeted climate goals. With numerous research projects on the deployment of new sustainable technologies in full swing, we now want to take the next step: NEFI Technology Talks bring together national and international efforts in the context of selected, industrial decarbonisation topics, synthesize findings and results, and form synergies to leverage further developments and drive them forward.

In this NEFI Technology Talk, possibilities are shown how heating and cooling networks can be decarbonised with the help of geothermal energy and industrial waste heat. In a series of lectures, not only the corresponding technologies will be presented, but also possible business models and holistic concepts based on successful examples.

Group of participants:
Industry and Municipalities

Language:
German

Welcome and opening

THOMAS KIENBERGER
Head of Chair of Energy Network Technology, Montanuniversität Leoben

Keynote: Geothermal energy as a central building block of the heat transition

EDITH HASLINGER
Center for Energy, AIT

Drilling planning and drilling technology in deep geothermal energy

OLIVER TAUSCH
RED Drilling & Services GmbH

Industrial waste heat potentials - possibilities of determination and case study

ANDREAS HAMMER
Montanuniversität Leoben

Techno-economic evaluation of waste heat integration

STEFAN REUTER
Center for Energy, AIT

High-temperature heat pumps

JOHANNES RIEDL
Center for Energy, AIT

Q&A and panel discussion

12.00 - 13.00
Lunch and conclusion

Scientific Board

Thomas Kienberger	Lehrstuhl für Energieverbundtechnik, Montanuniversität Leoben
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Christoph Brunner	AEE - Institut für Nachhaltige Technologien (AEE INTEC)
Gerald Steinmaurer	Center of Excellence, FH OÖ Forschungs und Entwicklungs GmbH

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I. Presentations: Energy Management and Flexibility Options

RECYCLING AND SECOND USE OF GREEN HYDROGEN FROM SEMICONDUCTOR INDUSTRY

Martin SAGMEISTER[1,*], Michael RICHTER[1], Markus SARTORY[1], Patrick PERTL[1], Alexander TRATTNER[1]

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[*] Corresponding author

Abstract: Sector-coupling is a key component for decarbonization of the energy sector, industry and mobility. Hydrogen plays a vital role in these sector-coupling strategies. Amongst many other applications it is used in semiconductor industry as a carrier gas for e.g. epitaxy processes. After processing this highly valuable energy carrier is either burned or diluted and released to the atmosphere. This paper describes the technical and ecological evaluation of four alternative utilization paths for the hydrogen that re-use it for energy production, mobility purposes, and internal recirculation, respectively. The implementation of the utilization as fuel for zero-emission mobility in the public transport sector is described in more detail. After semiconductor production the hydrogen will be collected, purified, compressed and utilized to operate up to 40 fuel cell busses as well as other heavy-duty vehicles and cars. Thus, this system cuts emissions by avoiding hydrogen emissions to the atmosphere and by replacing diesel in the transport sector.

Keywords: Green hydrogen; sector-coupling; zero-emission mobility; hydrogen busses; semiconductor industry

1 INTRODUCTION

In order to reach the ambitious targets for the reduction of greenhouse gases (GHGs) in the EU major emission cuts in all sectors will be necessary. Sector-coupling plays a key role in these reduction efforts and (green) hydrogen serves as an important link between sectors. Produced with electrolysers using renewable electricity it can serve e.g. as carbon-free feed-stock for the chemical industry, as substitute for coke in steel-making, as carrier gas for industrial purposes, as substitute for fossil fuels for providing heat, for energy storage, or as fuel for mobility purposes. This paper gives an example for such sector-coupling using hydrogen as carrier gas in a semiconductor processing plant of Infineon Austria Technologies and, subsequently, as fuel for fuel cell (FC) vehicles in Villach, Austria.

In their production plant in Villach, Infineon Austria Technologies produces semiconductors for industrial power control, automotive, and power & sensor systems producing over 8.7 billion chips in 2020/21 [1]. One of the processes used in production is epitaxial growth of silicon layers on wafers (epi-wafers) through chemical vapor deposition (CVD) where silicon is deposited on wafers by reducing silanes like trichlorosilane (HCl_3Si) at high temperatures using hydrogen as carrier gas and reducing agent [2].

Until now, this carrier gas was supplied in form of highly pure liquid hydrogen made through steam methane reforming and transported over 700 km via lorries from a supplier in Germany. The hydrogen is then additionally purified using a cryogenic purification process (cryogenic temperature swing adsorption, TSA) to a quality of 8.0 (99.999999%). It is then mixed with 40-60% inert gas, silanes and traces of dopant precursors containing P, B, or As. The hydrogen itself is not consumed during the epitaxy process. The subsequent waste gas additionally contains HCl as reaction product and from cleaning steps in the reaction chamber. The waste gas is scrubbed from environmentally harmful substances, diluted with air below the lower explosive level (LEL) of hydrogen and finally released to the atmosphere.

In order to change this use of emission intensive hydrogen, to avoid wasting a highly valuable energy carrier, and to increase security of supply, Infineon decided to produce their own, green hydrogen with an on-site electrolyser using renewable energy. In the framework of the "H2Pioneer - Pave the way for green hydrogen for early adopters in the light industry" (H2Pioneer) project funded by the Klima- und Energiefonds Austria (see Figure 1-1) four potential alternative utilization paths for the waste gas have been investigated.

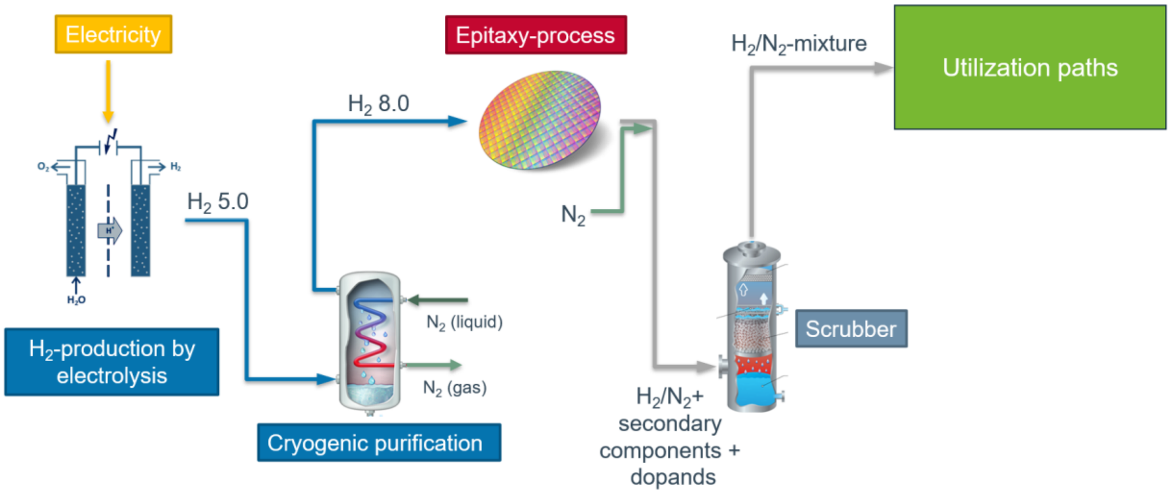


Figure 1-1: Schematic overview of the hydrogen production, purification, and utilization.

As a result of this project the decision was made to re-use the waste gas for zero-emission mobility purposes, especially in the public transport sector which is pursued in the framework of the "Reuse of Hydrogen for Bus Applications" (ReHyB) project funded by the Austrian Research Promotion Agency (FFG). Both projects are part of the H2Carinthia initiative and will be described in more detail in the following sections.

2 MATERIALS AND METHODS

One goal of the H2Pioneer project was to evaluate different paths for re-using the hydrogen from the epitaxy process in the semiconductor industry [3]. Four different paths were investigated, namely, using the hydrogen to drive a stationary internal combustion engine (ICE), purifying and using it in a stationary fuel cell for electricity generation, purifying and using it for H_2-moblitity at a hydrogen refuelling station (HRS), and internal recirculation of purified hydrogen back into the production process (see Figure 2-1).

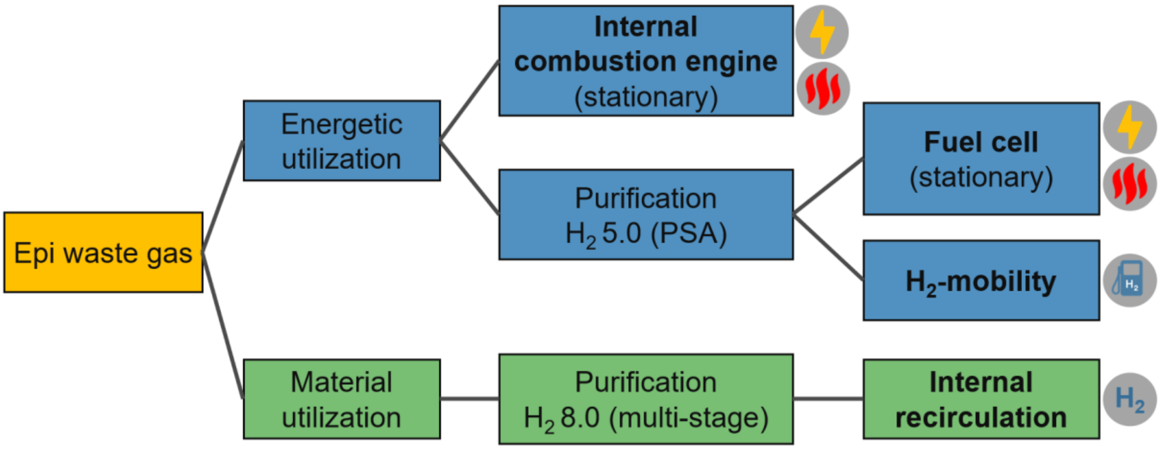


Figure 2-1: H_2 utilisation pathways for the epitaxy waste gas.

All four paths have been analysed on a technical and an ecological basis. The technical analysis was done on a conceptual level by means of mass and energy balances. Using characteristic curves of the major individual components zero-dimensional simulation models in MATLAB Simulink® have been implemented and analysed. Based on this analysis, an environmental analysis was accomplished by a calculation of greenhouse gas emissions following Greenhouse Gas Protocol guidelines [4].

Based on results from the H2Pioneer project re-use of the hydrogen for application in the mobility sector has been chosen as the path to be implemented through the ReHyB project. In this project coupling out and purification is simulated on 1D-/3D-computational fluid dynamics (CFD) simulations on component and system level. Data from real operation is then used for validation of these models. The HRS is simulated by model-based MATLAB Simulink tools. Instrumentation and control engineering will be done using Systems Modelling Language (SySML). For the operation of up to 40 busses in the public transport sector the hydrogen demand is simulated using longitudinal dynamic simulations with AVL CruiseM®.

3 RESULTS

3.1 Technical analysis of the utilization paths

For the utilization by means of a hydrogen ICE, the hydrogen is energetically converted into mechanical work and heat. The mechanical work is converted into electrical energy and can be used internally, for example, to operate the electrolysis. The heat can also be used internally for facility heating and reduces the heating demand that is currently provided by natural gas. This method requires the smallest number of components, namely a gas mixture system to secure a nitrogen content of at least 50% to avoid backfiring [5] and the ICE. Based on data from a hydrogen ICE *agenitor406* from the manufacturer *2G Energy AG* with a maximum power of 178 kW_{el} it was concluded that the electricity generated could lower the energy demand of the electrolyser by ca. 20%. Additionally, over 14 MWh of thermal energy per tonne of hydrogen could be utilized [3].

Utilization by a stationary PEM fuel cell could also generate electrical and thermal energy that can be used to cover part of the production plant needs. In contrast to the ICE, however, the PEM fuel cell can only be operated with high-quality hydrogen in accordance with the ISO 14687 standard. For this reason, the waste gas stream needs to be purified by e.g. a pressure swing adsorption (PSA). The system is more complex and consists of a compressor, a cooler for the compressor, a PSA and the fuel cell. The compression and purification use electric energy and the PSA can only recover a part of the hydrogen. Using data from a *PowerCell MS-100* system with a maximum power of 260 kW_{el} and a (simulated) hydrogen loss rate of 26% from the PSA (it has to be noted here that real PSA systems can have lower hydrogen loss rates in the range of 16%) a lower yield of electric power covering 11.5 % of the electricity consumption of the electrolyser can be achieved. The usable waste heat would amount to 10.9 MWh per tonne of hydrogen [3].

In case that the hydrogen is used for H_2-mobliity, the pre-treatment is very similar to the case of the stationary fuel cell. A first compression step including cooling of the compressor would be followed by purification using PSA. Subsequently, an additional further compression step to 350 bar and 700 bar for busses/heavy-duty vehicles and cars, respectively, is needed. The hydrogen could then be used to power e.g. fuel cell buses in public transportation. Assuming an average consumption of 30 l/100 km for a diesel bus and 7.5 kg_{H2}/100 km for a fuel cell bus one tonne of hydrogen can power latter bus for ca. 13300 km and replace 4000 liters of diesel.

Internal recirculation is the fourth alternative utilization path for the hydrogen. In this case it would in a first step be purified by a PSA yielding hydrogen with 5.0 quality. After this purification step it would have the same quality as the hydrogen from electrolysis and could be added to the hydrogen from the electrolyser. A second purification step using cryogenic TSA would then yield hydrogen of quality 8.0. If implemented, the hydrogen production would only need to replace the blow-off from the PSA.

3.2 Ecologic analysis

In accordance with the GHG Protocol [4], the environmental impact of the various epitaxy waste gas recovery concepts is evaluated by drawing up a CO_2 balance for the hydrogen path of the individual recovery methods. The total emissions (sum of direct and indirect emissions) of CO_2-equivalent emissions from the following areas are taken into account:

- Consumption of electrical energy during hydrogen production
- Hydrogen emissions during exhaust gas utilization
- Generation or consumption of electrical energy during waste gas utilization
- Generation of heat and replacement of natural gas during exhaust gas utilization
- Replacement of diesel by the use of hydrogen as a fuel

In order to achieve comparability of the greenhouse gas potential of the different forms of energy, all greenhouse gas emissions (GHG emissions) are converted to CO_2-equivalent emissions in the CO_2 balance. The factors for the CO_2-equivalents are summarized in Table 3-1.

Table 3-1: CO_2-equivalent emission factors of selected energy carriers [6] [7]

Emission factors (CO_2-equivalent of total emissions)		
Energy carrier	**kg_{CO2eq}/MWh**	**Source**
Electricity mix Austria	219	Umweltbundesamt [7]
Green electricity	14	Umweltbundesamt [7]
Natural gas	268	Umweltbundesamt [7]
Diesel (incl. 5.6% bio fuel)	321	Umweltbundesamt [7]
Hydrogen	174	Derwent et al. [6]

In order to assess the emissions for the different utilization paths in a first scenario the CO_{2eq} factor of the Austrian electricity mix (219 kg_{CO2eq}/MWH) is assumed. This represents the currently worst-case scenario in terms of emissions. Then the hydrogen production by means of electrolysis which accounts for high amounts of electrical energy consumption largely contributes to the CO_2 emissions (see Prod. in Figure 3-1). The provision of one tonne of hydrogen thus results in emissions of around 13.6 tonnes of CO_{2eq}

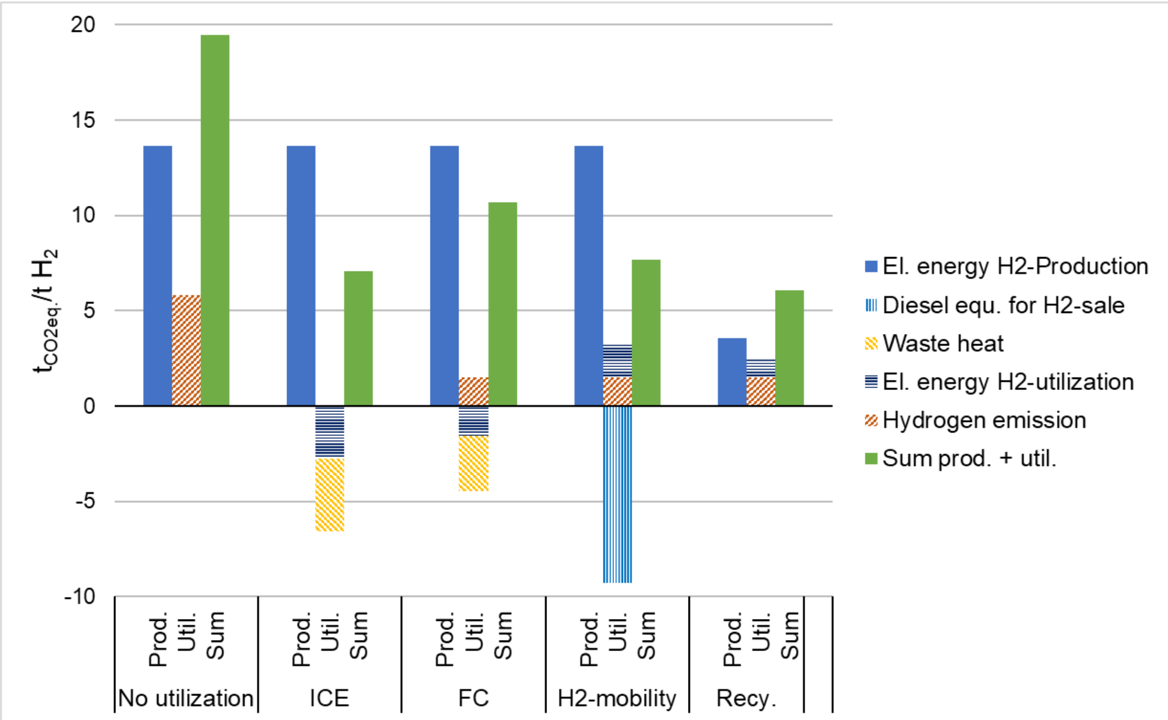


Figure 3-1: Emission balance of different utilization paths using the Austrian electricity mix.

Without a recycling method, all of the hydrogen is safely released into the environment after utilization (see Util. in Figure 3-1) and represents additional pollution, since hydrogen has an indirect greenhouse gas potential of 5.8 kg $CO_{2eq.}$/kgH_2 (equivalent to 174 kg$CO_{2eq.}$/MWh) [6] resulting in an additional emission of 5.8 tonnes of $CO_{2eq.}$ per tonne H_2. The indirect GHG potential results from a competing reaction to the decomposition of methane in the atmosphere. The case of hydrogen production via electrolysis and no further utilization (release to the atmosphere) is used as benchmark (see Sum in Figure 3-1).

In case of utilization through an ICE no hydrogen is released into the atmosphere and the obtained electrical and thermal energy reduces the emissions of hydrogen production and heating by natural gas, respectively, totaling in an emission reduction of ca. 64 % compared to the sum of the base scenario (assuming that accruing NOx emissions are avoided through aftertreatment). Due to the additional energy use for purification and compression as well as the hydrogen blow-off of the PSA, utilization through a fuel cell leads to an emission reduction of ca. 45 %. In the case of using the hydrogen for H_2-mobility, emissions from the additional energy use for purification and compression are more than offset by the replacement of diesel, resulting in a total emission reduction of ca. 60%. The internal recirculation of hydrogen yields the highest emission reduction in the range of 69%. Here the additional energy use for purification and compression is greatly offset by the recycling of the hydrogen and the accompanying energy savings at the hydrogen production via electrolysis.

If both the hydrogen production and all other electrical loads are considered to be powered by green electricity with an emission factor of only 14 kg_{CO2eq}/MWh (Umweltzeichen “Grüner Strom” in Austria [7]) the emissions of all utilization paths strongly decrease. The release of the hydrogen to the atmosphere is now the main contributor to emissions (except for the ICE). Through waste heat utilization and replacement of diesel, respectively, ICE, FC and H_2-mobility even abate more emissions than the production of the hydrogen emits in the first place (see Figure 3-2).

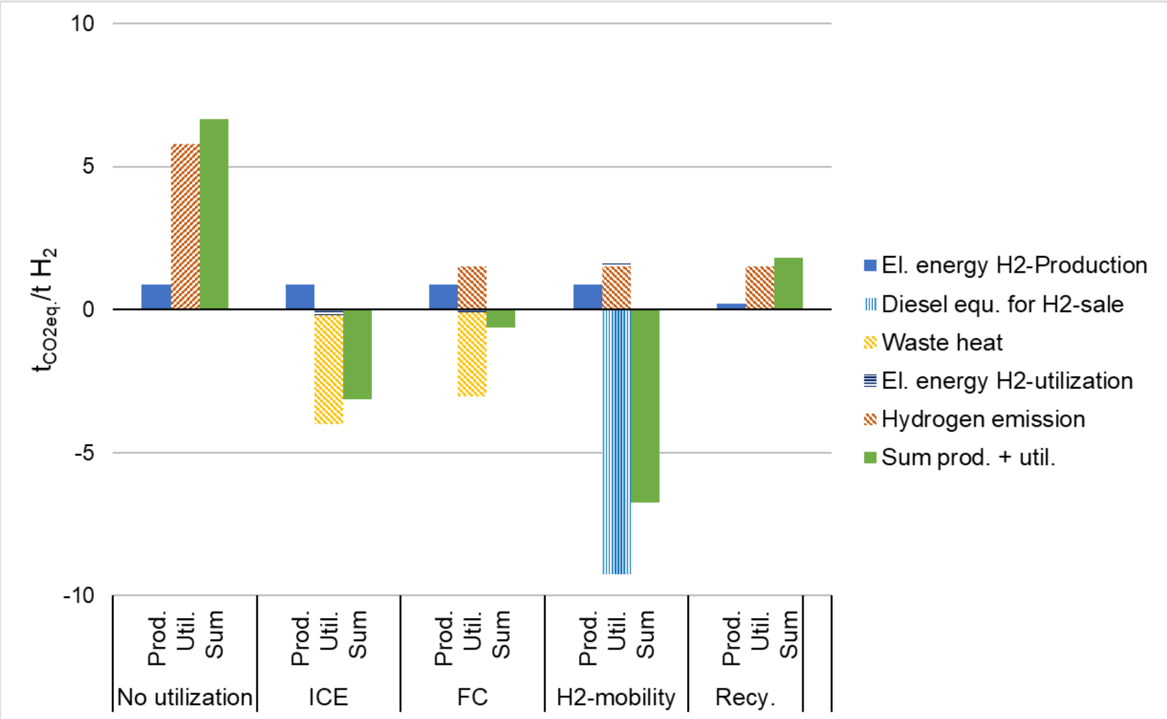


Figure 3-2: Emission balance of different utilization paths using green electricity.

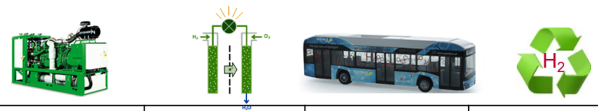
4 DISCUSSION

From a technical point of view all four utilization paths discussed above are realizable with existing technologies in principle although the technology readiness levels (TRLs) and degrees of innovation differ significantly. Hydrogen ICEs are already a well-established technology in this field thus their application poses a rather low degree of innovation. Reconversion of hydrogen to electricity via fuel-cells or using it in fuel-cell vehicles are also already established technologies, though the re-use of hydrogen from semiconductor industry would be a true innovation. Internal hydrogen recirculation also has not been implemented in semiconductor industry so far. One obstacle for this utilization path is the fact that some gas components from the epitaxy process like HCl or dopants cannot be measured online with an adequate resolution. Through multiple recycling steps they could accumulate in the hydrogen imposing a risk on the epitaxy production process. Since a negative influence on the sensitive process could prove to be very expensive such a risk will hardly be tolerated in semiconductor industry, prohibiting this path until adequate analytics for this purpose is available.

From an ecological point of view all four utilization paths lead to significant emission reductions. Depending on the assumptions for the emission intensity of the electricity mix the results for the emission reduction differ significantly, though. For the Austrian electricity mix (see Figure 3-1) the abatement is highest for internal recirculation due to the strong reduction of the need for energy intensive electrolysis in the hydrogen production. The paths using an ICE or using the hydrogen for zero-emission mobility both give similar, the use of a fuel-cell for reconversion into electricity gives the lowest emission reductions. If the use of green electricity is assumed (see Figure 3-2) emissions for all utilization paths as well as for no utilization are reduced dramatically and in three cases even leads to absolute emission savings if the replacement of natural gas for heating or diesel for mobility is considered. In this case the use for mobility purposes leads to the highest abatement followed by the ICE, the fuel cell and the recycling.

To fully evaluate the four presented hydrogen utilization paths an economic analysis would also be needed. This analysis strongly depends on assumptions for component and engineering prices and would go beyond the scope of this paper. Taking the results from the economic analysis of [3], though, some general remarks can be made. This work concluded that the fuel cell would under no scenario reach a break even while all other utilization paths would reach a break even in a range between 4 and 11 years with the ICE being the most profitable followed by recirculation and mobility.

Figure 4-1 gives a qualitative overview for the evaluation of the different utilization paths. Considering all three dimensions the fuel cell and the internal recirculation can both be excluded due to non-profitability and risks due to low TRL of available gas analysis systems, respectively. The ICE has many favorable features and the low degree of innovation is no show-stopper per-se. Nevertheless, use of the hydrogen from semiconductor production for zero-emission mobility has been chosen to be implemented due to its high potential for emission reduction and its degree of innovation to serve as a flagship project for the possibilities of sector-coupling.



Scale: 1 (bad) – 5 (good)	ICE	Fuel cell	H_2-Mobility	Recirculation
Criteria (technical, ecological, economic)	Evaluation	Evaluation	Evaluation	Evaluation
Period of amortization	5	1	3	4
CO_2 reduction (Austrian electricity mix)	4	3	4	5
CO_2 reduction (green electricity)	4	3	5	3
TRL	5	4	4	1
Innovation	1	4	4	5

Figure 4-1: Qualitative assessment of the four utilization paths proposed in this paper.

Presently, the implementation of this approach is being started in the framework of the ReHyB project. Figure 4-2 gives a schematic overview of the implementation concept. After pre-cleaning in a scrubber and drying of the waste gas the hydrogen/nitrogen mixture will be compressed in a first stage and pumped through a pipeline to a PSA situated at the HRS. After purification in the PSA the hydrogen with quality 5.0 is further compressed to be stored in low-pressure storage tanks.

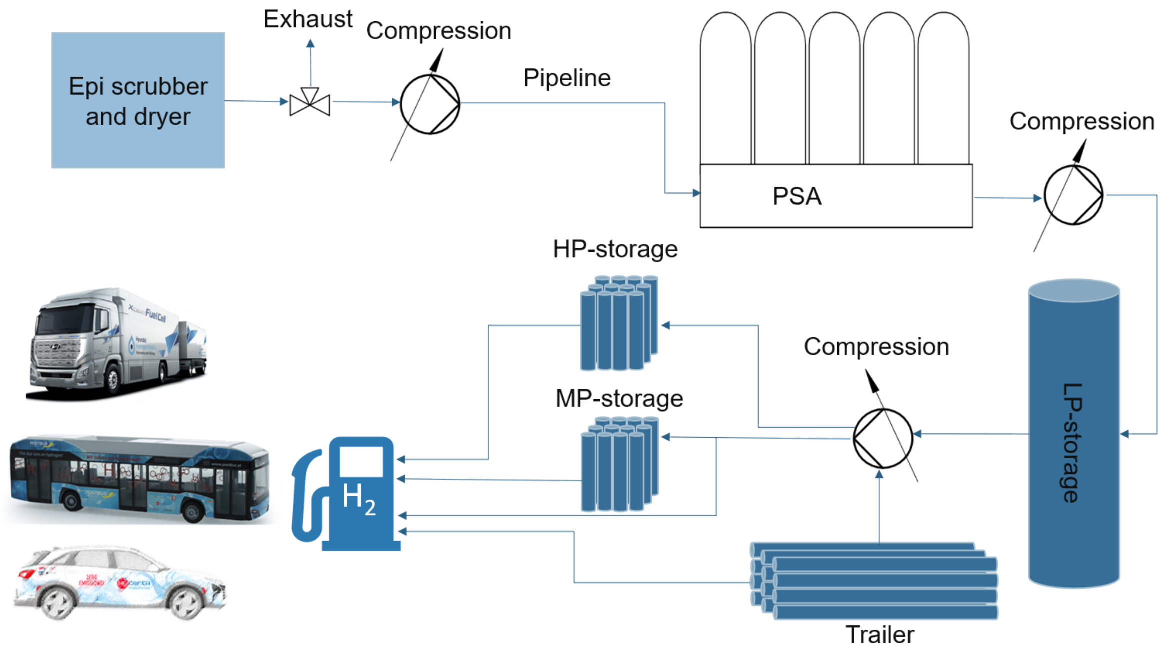


Figure 4-2: Schematic overview of the implementation of hydrogen collection, purification, compression and use in zero-emission mobility.

Another compression stage will raise the pressure to pressures apt to fill medium- and high-pressure storage tanks for refueling with a dual-use dispenser at 350 bar and 700 bar, respectively. A hydrogen trailer can also be connected to the HRS in order to increase security of supply e.g. in the case of maintenance works in the supply chain. By being close to three Austrian highways (A2, A10 and A11) and the “Baltic-Adriatic” TEN-T (Trans-European Transport Network) corridor the refueling station in Villach would also be placed in a strategically favorable place and filling a gap in the Austrian HRS network. The main use for the re-used hydrogen would be local public transport with a plan to fuel up to 40 FC-busses in and around Villach, decarbonizing most of the public transport in the region.

Another point to mention here is energy efficiency. One of the main arguments against hydrogen in the discussion fuel cell vs. battery vehicles is the lower round-trip efficiency of the former with a well-to-wheel efficiency in the range of 30%. The energy demand for re-using the hydrogen (drying, purification, compression) is less than 10 kWh per kg of hydrogen which has an energy density of 33 kWh/kg. With an efficiency of FC vehicles in the range of 50-60% the well-to-wheel efficiency would be up to 200% if the production of the hydrogen is fully accounted for in the semiconductor production already. This example underlines how wasteful it is to not re-use hydrogen whenever possible and the advantages of sector-coupling.

5 CONCLUSIONS

This paper showed that hydrogen can play a vital role in the decarbonization of our energy system through sector-coupling of energy systems, industry and mobility. All four presented paths for re-utilization of hydrogen from semiconductor industry show great potential to lower energy demand as well as GHG emissions. A technical, ecological and economic analysis of the four utilization paths conducted in the H2 Pioneer project and presented in the paper led to the decision to implement the re-use of hydrogen from industry for zero-emission mobility in the framework of the ReHyB project. Besides global GHG emission reduction, less emission of pollutants and noise will also benefit the health of the local population and increase the quality of living in the region.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] Infineon Technologies Austria AG, „www.infineon.com,“ [Online]. Available: https://www.infineon.com/dgdl/IFAT+Unternehmenspr%C3%A4sentation_DE.pdf?fileId=8ac78c8b7e7122d1017f26ee5cfa00f4. [Zugriff am 23 August 2022].

[2] Wikipedia, „Epitaxy,“ [Online]. Available: https://en.wikipedia.org/wiki/Epitaxy. [Zugriff am 23 August 2022].

[3] J. Trattner, „Energieeinsparungsmöglichkeiten durch Verwertung oder Aufreinigung von Wasserstoff in Abgasen von Industrieprozessen,“ Graz, 2021.

[4] „Greenhouse Gas Protocol,“ [Online]. Available: ghgprotocol.org. [Zugriff am 10 March 2021].

[5] J. Gausling, *H2-Motor - 2G Energy AG,* E-Mail Aug. 2019.

[6] R. Derwent, P. Simmonds, S. O'Doherty, A. Manning, W. Collins und D. Stevenson, „Global environmental impacts of the hydrogen economy,“ *IJNHPA,* Bd. 1, Nr. 1, p. 57, 2006.

[7] Umweltbundesamt, „Berechnung von Treibhausgas-Emissionen verschiedener Energieträger,“ [Online]. Available: https://secure.umweltbundesamt.at/co2mon/co2mon.html. [Zugriff am 25 August 2022].

[8] M. Klell, H. Eichsleder und A. Trattner, Wasserstoff in der Fahrzeugtechnik: Erzeugung, Speicherung, Anwendung, Wiesbaden: Springer Vieweg, 2018.

THE ROLE OF FORECASTING ENERGY CONSUMPTION AND DEMAND IN THE IRON AND STEEL INDUSTRY BY THE EXAMPLE OF AN ELECTRIC ARC FURNACE

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** **Winner of the Young Scientist Award**

Abstract: The iron and steel industry is one of the most energy intensive industries and therefore crucial for decarbonisation the industry sector. Especially electric steel mills, as alternative route to the blast furnace, offer potentials for electrification and integration of renewable energies. One part of the NEFI project DSM_OPT is the digitisation and operation optimisation of an electric steel mill. For this models of the main aggregates are build, with the aim of forecasting the energy consumption in a temporally resolved manner. These models are the basis for the subsequent operation optimisation. The electric arc furnace (EAF), with approximately 60 % of the average energy consumption, is the most energy intensive aggregate in the process chain. Therefore, modelling of this aggregate is of particular importance. This paper focusses on a literature review of the state of the art of modelling an EAF's energy consumption, data preparation and analysis of a specific EAF, and a benchmark model for a temporally resolved energy consumption forecast with a Long-Short Term Memory (LSTM) neural network. The main findings are that the EAF is characterised by a stochastic operational behaviour and that LSTMs are suitable for developing a benchmark for forecasting the temporally resolved energy consumption.

Keywords: Industrial Energy Systems; Iron and Steel Industry; Electric Arc Furnace; Forecast; Energy Consumption; Energy Demand; Data Analysis; Machine Learning; Neural Networks

1 INTRODUCTION

The international goals for reducing greenhouse gases are ambitious in every aspect. For example, the European Commission decided to reduce CO_2 emissions by 55 % until 2030. To be greenhouse gas neutral by 2050 is the centrepiece of the European Green Deal. [1, 2] With the intent of meeting the mentioned climate goals one necessary point to realise is the decarbonisation of the industry. Mainly speaking of the decarbonisation of energy intensive industries like iron and steel, pulp and paper, cement, ceramics, glass, (petro-)chemicals or foods and drinks. [3] Approximately 7 % of global greenhouse gas emissions (reference year 2021), equivalent to 2.6 Gt CO_2, are caused by the iron and steel industry. The production of crude steel can be divided into the primary production via blast furnaces and secondary production via EAFs. The main raw material for primary production is iron ore, while steel scrap is used as input material for secondary production. [4] In terms of energy consumption (and subsequently greenhouse gas emissions) secondary production is far more sustainable, using only 1/6 of energy compared to primary production. [5] In coming decades, the global share of steel production via electric arc furnaces is forecasted to increase: The International Energy Agency (IEA) investigated different scenarios regarding steel production routes in the next decades. One of them, the Stated Policies Scenario, expects a share of 47 %, while the Sustainable Development Scenario forecasts a share of 57 % via electric arc furnace route. Considering the share of 29 % in 2019, this consideration points out that the development of steel production will shift to the secondary production route in future. [4] One aim of the project DSM_OPT, embedded in the NEFI-network and "Vorzeigeregion Energie", is the digitisation and operation optimisation in terms of demand side management (DSM) in an electric steel plant, leading to an improvement of both energy efficiency and flexibility, a reduction of carbon dioxide emissions and energy costs.

The purpose of this paper is to describe the state of the art of modelling EAFs and the main findings of a data analysis from an Austrian EAF. Furthermore, to introduce a benchmark model for forecasting the temporally resolved energy consumption of an EAF. At the end of this project stage, there should exist forecast models of the temporally resolved energy consumption for all main aggregates of the steel mill. Operation optimisation works with future states, so for optimising the use of energy, energy costs or the reinforced implementation of renewables, we need to know how much energy is needed at which point in time in future from which aggregate. If available, this information can be used to react to fast changing market prices like electricity or for balancing between renewable generation and current demand. Therefore, it is necessary to build models in a highly temporally resolved manner. There have been several investigations following different approaches for modelling the energy consumption of EAFs or steel mills in general (genetic algorithms, neural networks, deep learning, regression analysis), but most of them worked with a much broader resolution (resolutions of one batch, one hour or one day [6–12]). Furthermore, most of them were never tested for predicting the energy consumption for future heats. The method used for creating a benchmark in this paper is a neural network called Long-Short Term Memory (LSTM).

In terms of data protection, all numbers and results in this publication are presented in a scaled manner.

2 MATERIALS AND METHODS

The following chapter describes the workflow for setting up a benchmark model for predicting the energy consumption of an EAF in a temporally resolved manner. In the first section a brief description of an EAF and its functionality is given, followed by the results of a comprehensive literature research about the state of the art of modelling the energy consumption of EAFs with additional focus on feature selection. Based on these insights, data preparation and analysis of historic data from an alternate current (AC) EAF in terms of a domain and correlation analysis was done, the latter using the software Visplore [13]. The last part of this work is a short introduction to neural networks, especially Long-Short Term Memory (LSTM) networks which are used for modelling the temporally resolved energy consumption of an EAF.

2.1 Electric Arc Furnace

Nearly 60 % of the average energy consumption are needed for the EAF operation at the investigated industrial site. The main task of the EAF is melting the inserted steel scrap. Energy is available through electricity (approx. 85 %) and natural gas (approx. 15 %). Electrical energy is submitted through three graphite electrodes and natural gas through three gas burners.

The process of melting the scrap has a batch wise character, meaning that the EAF gets sequentially charged with usually three baskets of scrap. The normal routine of one batch appears as follows: charging basket 1 – melting – charging basket 2 – melting – charging basket 3 – melting – fining – tapping. Because of this the energy demand curve has very characteristic peaks during the melting phase of each basket (see Figure 2-1). The three peaks show fluctuating maximum heights and durations in a batch wise comparison. This can be traced to the influence factors that change for every batch. These are mainly the scrap mass that gets charged, its quality, the homogeneity of the melt-scrap-mix inside the EAF, the injected oxygen, the lifecycle of electrodes and the experience or current decisions of operational staff at the site. Some of these factors are measured (e.g. scrap mass), some are measured but can't be brought into correlation. One example for this is the scrap quality. Although it is known by the operational staff it is not meaningful, because concentrations of chemical elements which can influence the energy demand differ significantly within one scrap quality class. Other influencing factors can't be measured (e.g. human decisions). Because of this, the initial situation for modeling an EAF and forecasting its energy consumption brings some challenges with it (more details in chapter 2.3).

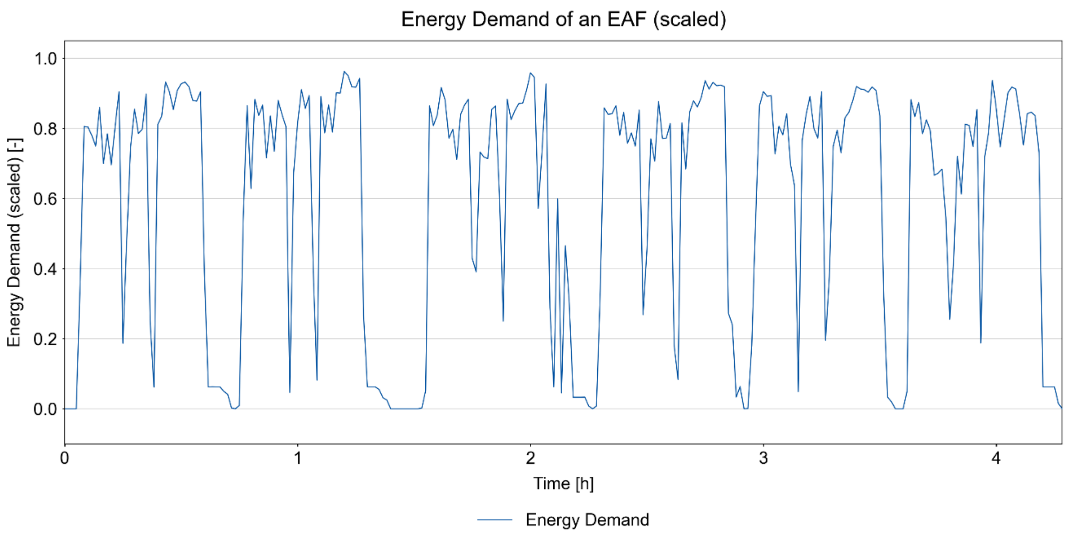

Figure 2-1: Energy demand of an EAF for six batches (one batch consists of three sequential peaks)

2.2 State of the Art of Modeling the Energy Consumption and Demand of EAFs

Chen et al. (2018) [9] forecasted the daily energy consumption of an EAF by using deep learning techniques. The used features for modelling are different scrap types, scrap mass, mass of additives (carbon, lime, dolomite), the tap-to-tap time (duration of a batch), the power-on time (during a batch) and oxygen demand.

Another approach for modelling the energy consumption of an EAF on a batch-base was done by Kovačič et al. (2019) [6]. The concerned steel mill produces flat steel, with more than 1,000 different steel grades and different chemical compositions. Data from 3,248 batches were collected during the year 2018 and used for building models with two different approaches: linear regression and genetic programming. During the different operating phases of the EAF (see chapter 2.1) different parameters were taken into account, including additives (coke, lime, dolomite), scrap type, scrap mass, oxygen demand, natural gas demand or maintenance and technological delays.

A comprehensive publication about existent statistical models for forecasting the batch-wise (kWh per heat) or specific (kWh per ton steel) energy consumption of EAFs was written by Carlsson et al. [10]. There it is mentioned that most of these models were never tested for future batches. This circumstance makes them nearly unusable for an application in a realistic environment. Existent methods for modelling EAFs include linear approaches like Multivariate Linear Regression (MLR) or Partial Least Squares (PLS) regression. For non-linear approaches Artificial Neural Networks (ANN), Deep Neural Networks (DNN), Random Forest and Support Vector Machines (SVM) are mentioned. Carlsson et al. [10] name five classes for relevant input features: Time (power-on time, power-off time, tap-to-tap time, etc.), chemicals (oxygen, chemical components of scrap, additives, etc.), temperatures (target temperature, temperature of melt, etc.), materials (scrap mix, slag, etc.) and other (heat demand for cold start, preheating scrap, delays, production strategies, etc.).

The same collective of authors published two other studies [14] [15] where they used ANNs for predicting the batch-wise energy consumption of an EAF. The produced steel quality in these cases was some sort of stainless steel and the modelling approaches include following statistical tools: Feature Importance, Distance Correlation and Kolmogorov-Smirnov tests. The authors emphasise the importance of a model's ability to forecast the energy consumption for future batches. In terms of choosing the right modelling approach, the authors state that Multivariate Linear Regression (MLR) is a sub-optimal tool for representing the non-linear behaviour of an EAF. For detecting the most important features for model building, a grid search was done. The chosen features follow the structure mentioned above. Furthermore, two common statements were derived: An increased amount of scrap leads to a higher energy consumption and an increased amount of oxygen leads to a decrease in electrical energy because of released oxidation energy of present chemical elements in the melt.

Gajic et al. [8] also used a neural network for predicting the specific energy consumption (kWh per ton stainless steel) considering the effect of chemical composition in the scrap mix. Data from 46 experimental runs were the input for the neural network which is implemented as multilayer perceptron with a 5-5-1 architecture. Their research shows that the carbon content in the end product has the highest effect on energy consumption. Other influencing factors like scrap density, chemical energy and final temperature of the molten steel were kept constant during the experimental runs.

A different approach was followed by Dock et al. [16], who generated temporally resolved generic synthetic load profiles with Markov chains for the main aggregates (including an EAF) in an electric steel mill. In a first step the energy consumption for an EAF-batch is determined, using a linear regression between inserted scrap mass and energy demand, derived from historic data. With this value, a specified tap-to-tap time and the transition probability matrices handed over to a Markov chain, a temporally resolved load profile can be generated.

2.3 Data Preparation and Analysis

Data analysis of the EAF is based on a 2-month data set from a specific EAF including process parameters (energy consumption, energy demand, temperatures, oxygen demand, coal demand, etc.) and batch information (durations of batches, duration of operating phases, scrap mass, etc.) from 1,800 batches in different time resolutions. At this point it has to be mentioned that the produced steel quality stayed the same for the investigated batches. The extracted data was cleaned from outliers with mainly domain knowledge, due to physical limitations (indicating measurement errors) and the 1.5-IQR-method by time series where it was possible. IQR stands for the Inter-Quartile Range, which describes the difference between the first quartile (Q1) and the third quartile (Q3) of the data. All data points under the lower bound (Q1 – 1.5 × IQR) or over the upper bound (Q3 + 1.5 × IQR) are considered as outliers. [17]

For easier handling, all of the available time series were converted to a temporal resolution of one minute. This step was carried out in Python using the libraries NumPy [18] and Pandas [19]. The decision which parameters are used for modelling is based on insights of data analysis, knowledge from literature (compare chapter 2.2) and data availability.

A correlation analysis with the already mentioned software Visplore was started trying to correlate the time series data of batch-wise energy consumption with different variables including tap-to-tap time or scrap mass. The Pearson Correlation Coefficient (PCC) of the parameter combination energy consumption vs. tap-to-tap time was 0.29 and energy consumption vs. scrap mass 0.39. This batch-wise approach was not very successful, as can be seen by the relatively low values for the PCCs. This can be explained as one batch in the EAF is characterized through different operating phases, which lead to a strongly varying energy demand (see Figure 2-1). Therefore, the data analysis was done in a finer resolution, concentrating on the different operating phases of the EAF. This approach has not been followed often as stated in literature. [10]

As the phases of melting basket 1, 2 and 3 and the fining phase are responsible for about 95 % of needed energy per batch, just these four phases were analyzed in the further attempt of the data analysis. In terms of duration of the different operating phases, following relationships could be detected: The relationship between duration of basket 1 and energy consumption is very weak (PCC = 0.09), the one between basket 2 and 3 and energy consumption is more significant (PCC = 0.86 and 0.80). In terms of fining the correlation is moderately weak, pronounced with a PCC of 0.30. Between scrap mass of basket 1 and energy consumption no correlation was found. Another picture showed the analysis between the scrap mass of basket 2 and 3 and energy consumption (PCC = 0.78 and 0.7). Between oxygen demand and energy consumption following correlations occur: basket 1: PCC = 0.13, basket 2: PCC = 0.75, basket 3: PCC = 0.73 and fining: PCC = 0.79. During the fining phase the reduction agent coal reacts with iron oxides and builds carbon monoxide, which foams the slag. The primary function of the slag is to remove unwanted components from the metallic melt. [20] The PCC between energy consumption and coal demand during fining phase is 0.45 (fining phase is the only phase where coal is used).

The above mentioned PCCs on the base of the operating phases are shown in Table 2-1. Grey coloured fields show strong correlations (≥ 0.7) and the term “not found” identifies parameter combinations where no correlation was found.

Table 2-1: Pearson Correlation Coefficients on the Base of operating EAF-Phases

Energy Consumption of	Duration Operating Phase	Scrap Mass	Oxygen Demand	Coal Demand
Basket 1	0.09	not found	0.13	-
Basket 2	0.86	0.78	0.75	-
Basket 3	0.80	0.70	0.73	-
Fining	0.30	-	0.79	0.45

All results of the correlation analysis were checked with a graphical evaluation of the scatter plots, as this step is necessary for sensible correlation analysis. All correlations above 0.7 showed clear dot clouds centered around the regression line. Correlations with coefficients below 0.5 displayed widely distributed dot clouds, underpinning the reasonableness of results.

Besides process parameters and input materials as influencing factors on energy consumption, unexpected maintenance works or production delays also have an impact, but measurement of these data is not possible and therefore not existent. Another point is the experience or intuition of operational staff, a factor that also can’t be measured.

2.4 Neural Networks

As a complete clarification of all influencing factors with a classical data analysis is, due to complex interactions and interdependencies in the operational behavior of an EAF, not possible, a modelling approach using machine learning may act as a reasonable tool for forecasting the energy consumption in a temporally resolved manner.

Besides traditional methods for forecast modelling like autoregressive or moving average models, data-driven approaches (machine learning) are able to learn relationships between different input parameters and the desired output parameter(s) out of data through implemented algorithms and enhance themselves with increasing experience (meaning more data). One type of machine learning models are neural networks, of which there are many different types available depending on the intended use [10, 21]. A neural network can depict systems with linear, but also with non-linear behavior. It consists of nodes, which are organised in layers and the simplest architecture is a feed forward neural network (see Figure 2-2).

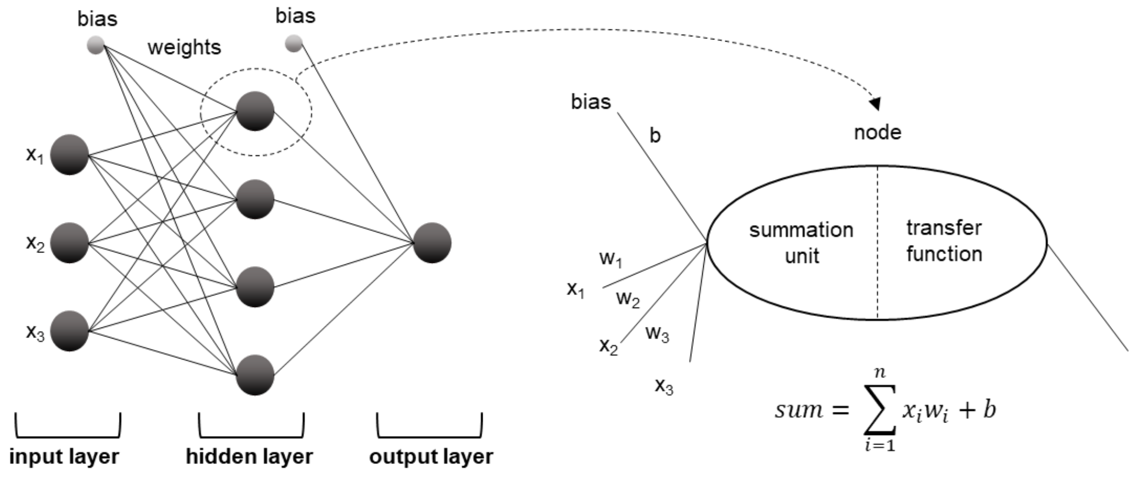

Figure 2-2: Schematic representation of a feed forward neural network and a node (based on [8], modified)

The number of input parameters (x_i) defines the number of nodes in the first layer, the so called input layer. All following layers until the last layer are hidden layers. These can contain a various number of nodes, depending on the complexity of the problem to be solved. The output layer is the last one in a neural network and the number of nodes correspond to the requested number of outputs. Each of the nodes perform a biased (b) weighted (w_i) sum of inputs and pass this into a transfer function to produce output. There are different kinds of transfer or activation functions, like Sigmoid, ReLU, Tanh or Linear. The learning takes place through iterative adjustment of the weights with the help of a backpropagation algorithm. [8, 9, 15]

It is necessary to split the historic data set in training, validation and test data. The share of training, validation and test data is not fixed, but the part of training data is the biggest. The model gets trained with the training data set, meaning the finding of mathematically describable relationships between input and output parameters. During this process the weights of the single nodes in the hidden layers get calculated. After training, the neural network gets validated before it’s exposed to new input values, from which it should predict a value of the desired output parameter based on the learned relationships. [8, 15, 22]

Besides modifying the input parameter set, the so called hyperparameters can be optimised before testing the neural network, which is commonly called grid search. Hyperparameters are topology parameters like the number of hidden layers and nodes or performance parameters like the learning rate. During grid search several neural networks with different settings of hyperparameters are created and tested regarding to their performance. [9, 15]

In terms of time series forecasting tasks, one kind of neural networks is particularly suitable. This type is called Long Short-Term Memory Recurrent Neural Network (LSTM-RNN). A Recurrent Neural Network is a dynamic classifier and therefore able to feed signals from past time steps back into the architecture. But RNNs are limited due to their time window they can look back into the past (approx. 10 time steps). LSTMs in comparison can take much more time steps (up to 1,000), depending on the complexity of the problem, into account. [21]

The here presented LSTM works as benchmark model for testing the usability of modelling the temporally resolved energy consumption of the EAF for future batches under perfect forecast conditions, meaning known values for input parameters. As input parameters the following ones are used: scrap amount (per basket), duration of operating phases (preparation, basket 1, basket 2, basket 3, fining, tapping), oxygen demand per phase, coal demand per phase and melting temperature. After performing a grid search for optimising the hyperparameters, the architecture of the LSTM consists of one hidden layer with 70 nodes and a linear activation function. The programming language for building the model was Python and used libraries were NumPy [18], Pandas [19], Scikit-Learn [23], Tensorflow [24] and Keras [25]. The training and execution of the model runs on a graphic card from NVIDIA with 8 GB RAM and 6,144 CUDA computing units. The prediction horizon covers one week and the temporal resolution is one minute.

3 RESULTS

The result of the benchmark prediction of the mentioned LSTM in chapter 2.4 is displayed in Figure 3-1 and shows the forecasted energy demand curve (in blue) and the real energy demand curve (in red) for 5 exemplary batches. As error measures the average energy demand (E_{avg}), maximum energy demand (E_{max}) and the Root Mean Squared Error (RMSE) for a 15-minute time window of these 5 batches were used (see Table 3-1).

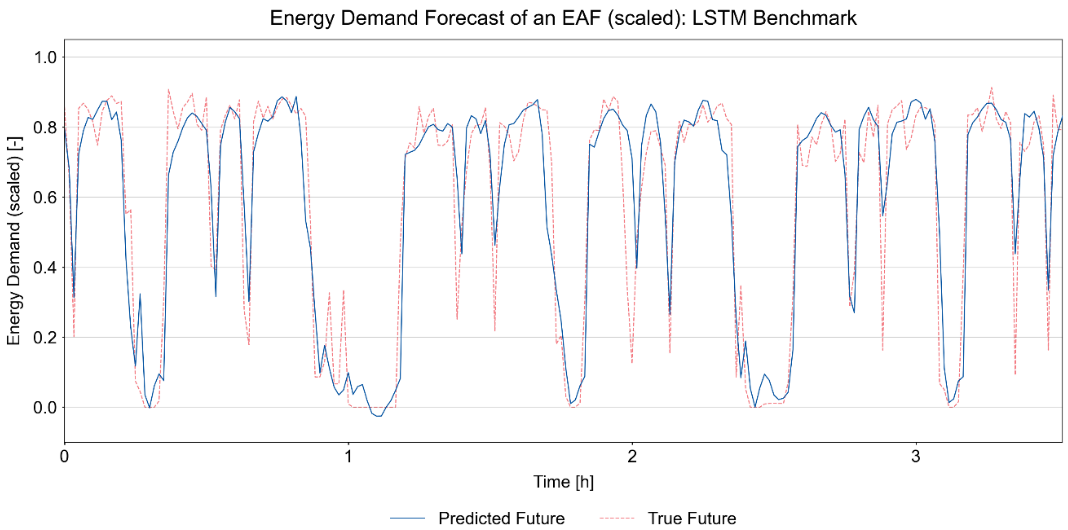

Figure 3-1: Energy Demand Forecast of an EAF (scaled): LSTM Benchmark, exemplary for 5 batches

Investigations of E_{avg} show that the LSTM generally predicts a higher value than in reality, while the predicted values for E_{max} are generally lower than in reality. The 15'-RMSE for the displayed batches lies, related to the true E_{avg}, in the range of 10-13 %. The computational time of this benchmark LSTM is exceedingly fine with the used hardware, meaning that the calculation time for a prediction horizon of one week with a temporally resolution of one minute is below 60 seconds.

Table 3-1: Error Measures of LSTM Benchmark

	Δ Predicted and True Mean Value in %	**Δ Predicted and True Maximum Value in %**	**15’-RMSE referred to True Mean Value in %**
Batch 1	0.86	-4.87	12.03
Batch 2	-0.96	-2.46	10.88
Batch 3	-2.20	-0.64	12.03
Batch 4	3.87	-2.29	12.97
Batch 5	4.30	0.96	11.17
Mean	1.17	-1.86	11.82

4 DISCUSSION

Some anomalies, which occurred during data analysis, are discussed in the following paragraphs. The correlation between energy consumption and duration of operating phases or scrap mass during basket 1 is weak or not existent in comparison to basket 2 and 3 and findings from literature [14, 15]. One explanation for this anomaly could be that the melt-scrap-mix inside the EAF is the most heterogeneous during the melting process of basket 1 as it is the beginning of a batch.

Another distinctive feature is the oxygen demand: First of all, oxygen functions as accelerator in the scrap melting process. Through occurring oxidation reactions from chemical elements in the scrap material, heat is emerging. Leading to a lower amount of energy needed for the melting process. [14, 15] The correlation between basket 1 and oxygen demand also shows a very low-pitched positive correlation. But against statements from literature, the other two baskets and the fining phase show a significant positive correlation.

In terms of the results of the LSTM benchmark model, following conclusions have been made: As one can see in Figure 3-1 the predicted energy demand curve is smoother than the real one and random looking oscillations can’t be learned by the neural network. The reason for this lies with a high probability in the earlier mentioned feature problem that not all relevant features are or can be measured and used as input for the LSTM (see chapter 2.3). In consideration of the circumstances in combination with the error measures it can be said that the methodical approach for creating a benchmark is successful. At this point it has to be mentioned, that this scenario is a so called perfect forecast scenario, where all values for input parameters are known. Also, data-driven approaches like neural networks are only as good as the used data, therefore limited by its availability and quality.

Further research has to be done regarding predicting the energy consumption of future batches under realistic conditions, as this is needed for a successful operation optimisation. The challenge with this lies in the unknown values for the input parameters of upcoming batches, meaning that the neural network, in this methodical approach, doesn’t have any input and therefore can’t make a prediction. This circumstance is due to process inherent logistics and procedures. For solving this issue a hybrid approach may be successful, combining data-driven neural networks with Markov chains for considering stochastic features.

Because of the highly oscillating operational behaviour of the EAF, it is assumed that there’s always a trade-off between forecast accuracy and prediction horizon to be made. Meaning that the prediction horizon for a reasonable temporally resolved energy consumption of the EAF may be very short and covers just a few hours in the future.

Overall goal for the following operation optimisation is an energy cost reduction of 2-5 % per tonne of produced steel. Furthermore, the project contributes to the electric steel mill's goal of saving 10 % of today's net energy consumption per tonne of steel by 2025.

5 REFERENCES

[1] Europäische Kommission, *Für Klimaneutralität bis 2050*. Brüssel, 2020. Accessed: May 19 2022. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/de/ip_20_335

[2] Europäische Kommission, *Lage der Union*. Brüssel, 2020. Accessed: May 18 2022. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/de/ip_20_1599

[3] T. Gerres, J. P. Chaves Ávila, P. L. Llamas, and T. G. San Román, "A review of cross-sector decarbonisation potentials in the European energy intensive industry," *Journal of cleaner production*, vol. 210, pp. 585–601, 2019, doi: 10.1016/j.jclepro.2018.11.036.

[4] IEA, "Iron and Steel Technology Roadmap: Towards more sustainable steelmaking," IEA, Paris, 2021. Accessed: May 23 2022. [Online]. Available: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf

[5] IPCC, "Climate Change 2022: Mitigation of Climate Change: Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge, UK, New York, NY, USA.

[6] M. Kovačič, Klemen Stopar, R. Vertnik, and B. Šarler, "Comprehensive Electric Arc Furnace Electric Energy Consumption Modeling: A Pilot Study," *energies*, 2019.

[7] O. Kahrs, G. Dünnebier, S. Krämer, and h. Luft, "Batch-Prozessführung: Potenziale und Herausforderungen," 2010. [Online]. Available: https://www.namur.net/uploads/tx_press/atp_01_02_2011_Batch_Kahrs.pdf

[8] Dragoljub Gajic, I. Savić-Gajic, I. Savic, O. Georgieva, and S. Gennaro, "Modelling of electrical energy consumption in an electric arc furnace using artificial neural networks," *undefined*, 2016. [Online]. Available: https://www.semanticscholar.org/paper/Modelling-of-electrical-energy-consumption-in-an-Gajic-Savi%C4%87-Gajic/367a455c86dac1a553f728e323b5e7c3744f27ca

[9] Chong Chen, Y. Liu, Maneesh Kumar, and Jian Qin, "Energy consumption modelling using deep learning technique — a case study of EAF," *undefined*, 2018. [Online]. Available: https://www.semanticscholar.org/paper/Energy-consumption-modelling-using-deep-learning-%E2%80%94-Chen-Liu/562a6813975d067de7b4bb9a6ecb8db454b4f068

[10] L. S. Carlsson, P. B. Samuelsson, and P. G. Jönsson, "Predicting the Electrical Energy Consumption of Electric Arc Furnaces Using Statistical Modeling," *metals*, no. 9, 2019.

[11] R. Klempka and B. Świątek, "In Day-Ahead electricity load forecasting," *undefined*, 2009. [Online]. Available: https://www.semanticscholar.org/paper/In-Day-Ahead-electricity-load-forecasting-Klempka-%C5%9Awi%C4%85tek/9d7371204322012bbe8685229a825aa8c2cc532d

[12] F. Butt, Lal Hussain, A. Mahmood, and K. J. Lone, "Artificial Intelligence based accurately load forecasting system to forecast short and medium-term load demands," *undefined*, 2020. [Online]. Available: https://www.semanticscholar.org/paper/Artificial-Intelligence-based-accurately-load-to-Butt-Hussain/b2b86ab263aaee59351fbaeda779f42da93c2149

[13] Visplore, *Visplore – Software for Visual Time Series Analysis*: Visplore GmbH, 2020. Accessed: Aug. 2 2022. [Online]. Available: https://visplore.com/

[14] Leo Carlsson, P. Samuelsson, and P. Jönsson, “Using Statistical Modeling to Predict the Electrical Energy Consumption of an Electric Arc Furnace Producing Stainless Steel,” *undefined*, 2019. [Online]. Available: https://www.semanticscholar.org/paper/Using-Statistical-Modeling-to-Predict-the-Energy-of-Carlsson-Samuelsson/0ef9f96b4a3cb0f7c93ea9aba203fca359d353fc

[15] L. Carlsson, P. Samuelsson, and P. Jönsson, “Using Interpretable Machine Learning to Predict the Electrical Energy Consumption of an Electric Arc Furnace,”

[16] J. Dock, D. Janz, J. Weiss, A. Marschnig, and T. Kienberger, “Time- and component-resolved energy system model of an electric steel mill,” *Cleaner Engineering and Technology*, vol. 4, October, 2021. [Online]. Available: https://pure.unileoben.ac.at/portal/de/publications/time-and-componentresolved-energy-system-model-of-an-electric-steel-mill(45eda8ec-64be-4cf5-a953-ca2e3ed264f2)/export.html

[17] S. Baumann, M. Gnisia, and et al., “Identifikation und Behandlung von Ausreißern in Flugbetriebsdaten für Machine Learning Modelle,” [Online]. Available: https://www.dglr.de/publikationen/2018/480169.pdf

[18] *NumPy: Fundamental Package for Scientific Computing with Python*, 2005. Accessed: Aug. 2 2022. [Online]. Available: https://numpy.org/

[19] *pandas - Python Data Analysis Library*, 2008. Accessed: Aug. 2 2022. [Online]. Available: https://pandas.pydata.org/

[20] Stahlinstitut VDEh, *Stahlfibel.* [Online]. Available: https://www.amazon.de/Stahl-Fibel-Stahlinstitut-VDEh/dp/3514007411 (accessed: Jun. 29 2022).

[21] R. C. Staudemeyer and E. R. Morris, “Understanding LSTM - a tutorial into Long Short-Term Memory Recurrent Neural Networks,” Sep. 2019. Accessed: Apr. 7 2022.

[22] Y. Wang *et al.,* “Short-term load forecasting of industrial customers based on SVMD and XGBoost,” *International Journal of Electrical Power & Energy Systems*, vol. 129, p. 106830, 2021, doi: 10.1016/j.ijepes.2021.106830.

[23] *scikit-learn: Machine Learning in Python*, 2007. Accessed: Aug. 2 2022. [Online]. Available: https://scikit-learn.org/stable/index.html

[24] TensorFlow, *TensorFlow.* [Online]. Available: https://www.tensorflow.org/ (accessed: Aug. 2 2022).

[25] *Keras.* [Online]. Available: https://keras.io/ (accessed: Aug. 2 2022).

[26] A. Bhaskar, R. Abhishek, M. Assadi, and H. N. Somehesaraei, “Decarbonizing primary steel production : Techno-economic assessment of a hydrogen based green steel production plant in Norway,” *Journal of cleaner production*, vol. 350, DOI: 10.1016/j.jclepro.2022.131339, 2022, doi: 10.1016/j.jclepro.2022.131339.

FLEXIBILITY IDENTIFICATION OF AN INDUSTRIAL PRODUCTION

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Abstract: The rising share of renewables and consequently an increasing number of volatile power generators are challenging our power grid systems. To ensure a secure power transmission in the future, additional measures for balancing supply and demand and the management of congestion are required. While balancing tasks are currently mainly performed by controllable generation and storage units, it is crucial to exploit new options and flexibilities on the demand side. Large consumers such as the energy extensive industries show promising potential to provide the required flexibility. However, in industrial companies the compliance with the production is of superordinate priority, thus the identification of technically available and economic feasible power consumption flexibilities constitutes a complex task. This contribution addresses this issue and presents new a methodical approach for identifying and quantifying marketable flexibilities in industrial energy systems based on mathematical optimization. In application on a real industrial use case from the paper industry, flexibility potentials are identified and evaluated.

Keywords: Industrial energy systems; Optimization; MILP; Demand side management; Flexibility

1 INTRODUCTION

Following the plan from the Austrian government, the total amount of MWh produced by photovoltaic and wind energy per year will increase by more than 600% and 200% until 2030 [1]. Their fluctuating power generation forces grid operators to intervene since generation and demand must be always balanced.

Secondly, the more distributed renewables and the rising number of “new” consumers such as electric vehicles are responsible for the higher occurrence of congestions in the grid. To prevent these kinds of congestions, the transmission system operator can change the dispatching of power plants, which is called redispatch. In 2021, the Austrian Transmission system operator (APG) had to interfere on 241 days to prevent congestions and maintain security of supply [2].

Both balancing and redispatch services are nearly always provided by large power plants. Particularly conventional thermal power plants are effective when it comes to providing flexibility to the power system, since they can ramp-up, or down their power output relatively fast. To reduce carbon emissions and gas dependence, these kinds of power plants will have to be replaced at some point, leaving our power grid system in dire need of flexibilities, that can be provided to the grid operator.

Since flexibility can be provided by electricity producers as well as consumers, energy intensive industries have a high potential of offering flexibility services in the future. In fact, they can already sell their flexibilities in balancing markets. But participating in these kinds of markets is still quite challenging, mainly because of the following reasons:

1. **The barrier of entry is very high**. In order to participate in any balancing market the providing assets have to be prequalified, to prove its capability (e.g. ramp-up/down times) of providing the needed flexibility.
2. **The minimum size** in terms of MW that can be sold at these markets are quite high. Generally, smaller assets can be pooled to form a so-called virtual power plant, allowing to thus reaching the minimum requirements.
3. **Operational security**: Providing flexibility should not interfere with production plans. Especially for short term delivery, it is important that the production chains and batch processes remain manageable without additional cost.
4. **Identifying and evaluating flexibilities**: The requirements of evaluation the flexibility in industrial energy systems can be quite complex. E.g., Identifying possible timeslots, their flexibility potential and related cost can become nearly impossible without mathematical methods.

This contribution presents a new method based on mathematical optimization that enables to identify and quantify marketable flexibilities. The identification and quantification of existing flexibilities is demonstrated on the basis on a specific real industrial use case from the paper industry.

2 MATERIALS AND METHODS

Use Case: An industrial production including two factories located close together are considered. The energy supply systems of both factories, connected to the high-voltage grid via a common transformer, are very similar. At one factory where only paper is produced, there are gas-fired steam boilers, generating live steam to supply two backpressure turbines. After the live steam has been expanded to generate electricity, the low-pressure steam is available to supply heat to paper machines and other facilities. Alternatively, the turbines can also be bypassed via reducing stations, which provides substitutive flexibility in the company's on-site energy generation. In addition, steam accumulators connected with municipal heating systems compensate fluctuations in on the thermal side. Moreover, electricity is also produced by a run-over-river hydropower plant, which also has limited, but controllable flexibilities through flow control. Limitations arise due to the production capacities of the individual components, systems and, especially from water supply and condensate recirculation. As the plant was designed “heat driven”, the electricity generated on site is not sufficient to cover the entire electrical demand of the production site, so the residual load is covered by the electricity grid. As a result, grid-based energy is purchased in the form of gas and electricity. The other plant is very similar in design, including a pulp production facility in addition. Pulp production mainly requires heat, which is covered to a large extend by the chemical recovery process, where spent liquor is fired in a specialized boiler to recover the cooking chemicals. While generating steam from liquor reduces the need for gas as a fuel, only as much liquor can be burnt as is produced by the pulp production. Still, there are hardly any immediate bottlenecks in the process and a number of flexibilities were identified.

Operational Considerations: Before the method can be introduced in detail, the operational consideration and its boundary conditions are addressed. From an operational perspective, flexibilities are necessary in order to adapt to the fluctuating energy requirements of production and for compensating production-related outages and shutdowns. The existing flexibilities are rarely exploited. Temporarily not required flexibilities for operational purposes can provide additional energy services. However, compliance with the production plan is of superordinate priority. Thus, we define a baseline as an optimal mode of operation ultimately reflecting the minimum of energy purchase costs to commit with the energy requirements of the processes with subject to technical constraints. This baseline scenario includes the corresponding control sequences, operating conditions and system states of all individual units u as time series. Considering power systems, the provision of balancing services and congestion management is of high necessity to ensure a secure operation of power grids, especially considering an increasing volatile renewable feed-in.

Consequently, among the possibilities for industrial enterprises of exploiting internal flexibilities, the provision of balancing services in power grids appears most promising. Therefore, in the following, the adaptability for changing the electricity consumption plan in relation to this baseline determines the flexibility of a system. Thereby, positive flexibility means a reduction in power consumption compared to baseline, negative flexibility means an increase. Determining free exploitable flexibilities, especially considering complex industrial plants with many different components and energy-consuming processes is a quite comprehensive task. Moreover, flexibilities are subject to economic framework conditions.

Problem statement: Following the above explanations, the problem can be split into two parts. The first part is the determination of the baseline as the most cost-effective plant operation to meet the energy requirements of the production processes. In the second part, possible deviations from the baseline are to be identified. However, not exclusively the technically possible flexibilities are of interest, but particularly those that that are profitable with additional revenues from the redispatch market.

Basic approach: The problem definition already indicates the use of mathematical optimization as fundamental methodical solution approach. Especially in application on optimization problems for industrial multi-energy systems, Mixed-Integer-Linear-Programing (MILP) approaches have proven to be a very suitable modelling as well as solution method and is thus adopted here. Since, from an operational perspective, it is purely a matter of maximizing economic benefits, the problem corresponds to the determination of the economic dispatch, which is formulated as unit commitment problem. The plant model of the use case is composed in a modular way based on its individual components according to the energy hub concept [3]. For the generation units, operational constraints like ramping, standstill, shut-up, shutdown are considered following the formulations presented in [4]. The general modeling approach and component modelling formulations base on contributions of [5] and [6].

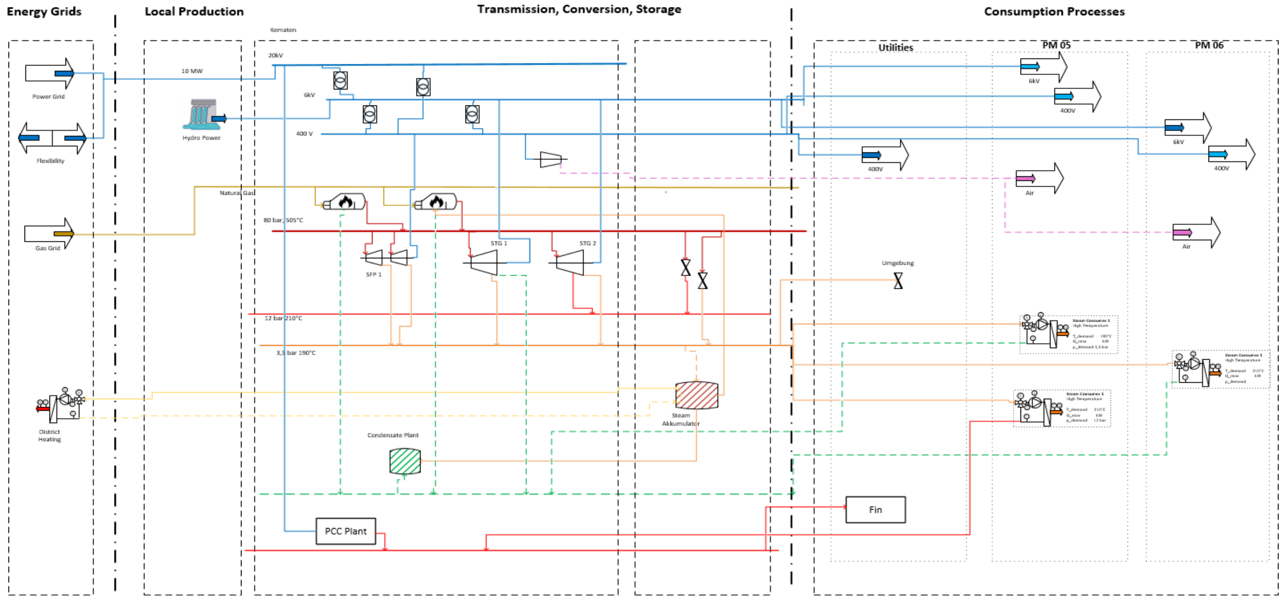

Figure 1: Model of the paper and pulp mill from production site 2

The optimization problems of the two methodical parts differ only slightly with subject to the objective function Eq. (1) and constraints Eq. (2, 3). In the plant model, depicted for site 2 in Figure 1, there are two (external) power sources. One representing the ordinary power supply, purchased at spot market tariffs and the other one representing the potential flexibility provision. In the consideration of the first step, the flexibility component is switched off (represented by Eq. (2) in the mathematical model listed below) and the main costs result from the energy purchase of electricity and gas. Operational expenditures and other incurring costs account for an insignificant proportion of the total. The essential result of the first part is the power consumption schedule, as time series of the ordinary grid power supply component, which is in the following considered as baseline power purchase.

In the second step, the flexibility component is switched on by Eq. (2). As flexibility is considered as deviation from the baseline power purchase, the component representing the ordinary power supply purchased on the spot market must exactly fulfil its schedule determined in the first stepwhich is represented by Eq. (3). Consequently, due to the introduction of Eq. (3), the second term in the objective function has no effect on the objective value and is therefore deactivated. It is important to remember that only the time series of the grid supply component is equal within the two methodical steps, while all other components may differ in their operation modes.

For the flexibility component, prices as well as the specification of the direction (positive/negative) are applied. The objective function takes a different form, which can be regarded to maximize the additional revenue facilitated by the introduction of the by the flexibility component. The main result is the daily profile of maximum economic reasonable and technical feasible power consumption flexibility. Together with the price assumptions, the flexibility calculated in this way represents the marketable flexibility potential under the given boundary conditions. In the subsequently listed mathematical formulations, binary auxiliary parameters have been used to activate or deactivate certain constraints and terms. The parameter δ is 0 in the case of baseline calculation and 1 in the case of flexibility calculation. Since positive and negative flexibility are not determined at the same time in the approach, the parameter ε is used to distinguish between them. If ε is 0, positive flexibility is determined; if ε

is 1, negative flexibility is determined. All other abbreviations and indices used in the mathematical model are listed in **Table 1**.

$$min \sum_{t=1}^{T} \left(p_G^t\, \boldsymbol{e_G^t} + (1-\delta) p_{EL}^t\, \boldsymbol{e_{EL}^t} - \delta\, p_{EL,Flex}^t\, \boldsymbol{e_{EL,Flex}^t} - p_{DH}^t\, \boldsymbol{e_{DH}^t}\right) \Delta t + \sum_{\boldsymbol{u}} \boldsymbol{C_{OM}^u} \tag{1}$$

$$\delta\,(\varepsilon - 1)\, P_{max,flex,pos}\, \Delta t \leq \boldsymbol{e_{el,flex}^t} \leq \delta\, \varepsilon\, P_{max,flex,neg}\, \Delta t \tag{2}$$

$$\delta\, \boldsymbol{e_{EL}^t} = \delta\, e_{EL,baseline}^t \tag{3}$$

Table 1: Abbreviations and Indices used in Eq. (1-3)

	Abbreviations			*Indices*	
p	*price in €/MWh*	*t*	*time*	*G*	*Gas purchase*
e	*energy in MWh/h*	*pos*	*positive*	*EL*	*Electricity purchase*
P_{max}	*maximum capacity in MW*	*neg*	*negative*	*DH*	*district Heating feed-in*
Δt	*time step in h*	*flex*	*flexibility*	*OM*	*Operation & Maintenance*
C	*costs*	*u*	*units*	*baseline*	

Assessment and Evaluation Scenarios: Apart from the technical parameters of the individual components, the boundary conditions of the use case include, on the one hand, the energy requirements of the processes that must be precisely fulfilled. On the other hand, price profiles are specified for the procurement and feed-in of grid based energy sources. The analysis period refers to 24 hours divided into 96 periods of 15 minutes. In order to provide a more comprehensive basis for the assessment and identification of flexibilities, different base price scenarios, suggested by the industrial company, were investigated. In the two low price scenarios, which are shown in Figure 2, a constant gas price of 120 €/MWh is assumed. For the electricity price, in the one case a variable daily profile with an average price of also 120 €/MWh is supposed, in the second case the electricity price is assumed to be constant as well. In the high price scenarios depicted in Figure 3, the gas price is constant at 160€/MWh and the electricity price profile is scaled up to an average price of 300€/MWh and is also considered once variable and once constant.

Subsequently, flexibilities are determined on the basis of different price tariffs, which are assumed to be constant over the entire period. These are for positive flexibility 10€/MWh, 100€/MWh, 300€/MWh and 500€/MWh and -100€/MWh, -20€/MWh, and 110€/MWh for negative flexibility. The special circumstance of considering negative prices in the case of negative flexibility will be addressed in the discussion in more detail.

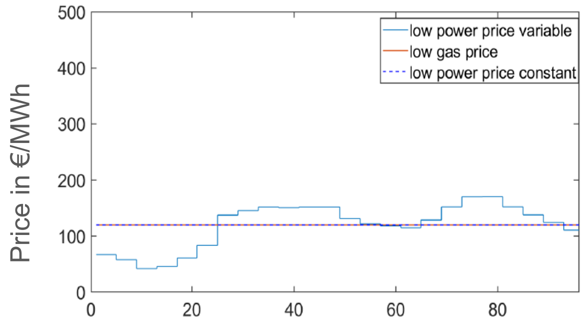

Figure 2: low price scenario energy costs

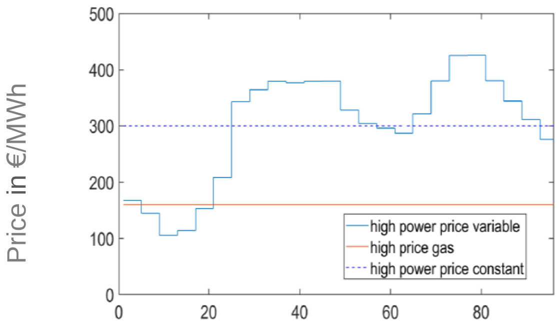

Figure 3: high price scenario energy costs

3 RESULTS AND DISCUSSION

The figures 4-7 show a comparison of the power and gas consumption profiles of the different baseline scenarios, separated into variable and constant electricity price scenarios.

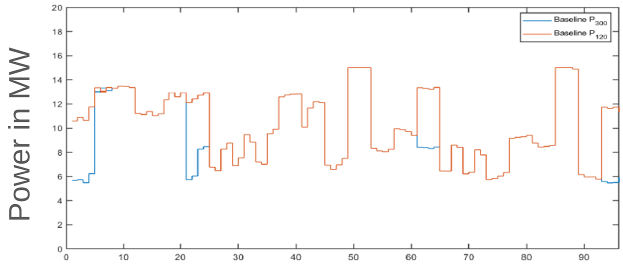

Figure 4: power supply baseline at variable electricity prices

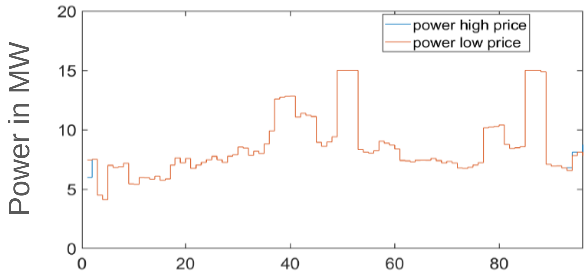

Figure 5: power supply baseline at constant electricity prices

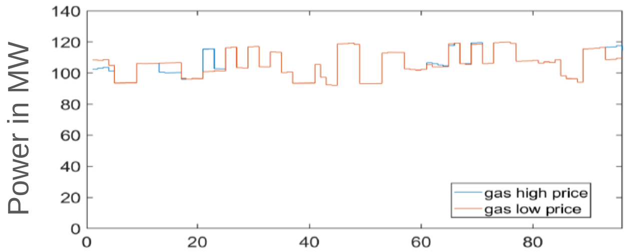

Figure 6: gas supply baseline at variable electricity prices

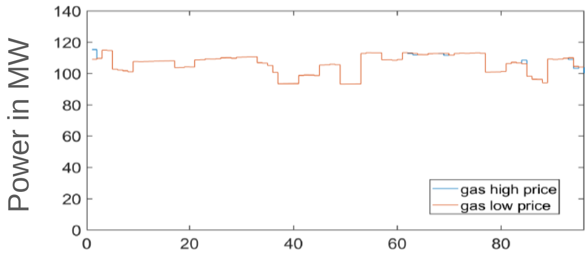

Figure 7: gas supply baseline at constant electricity prices

Based on the price scenarios introduced in the last section, which differ in behavior, magnitude, and in the relation to each other, the effects of the energy price profiles on the energy consumption profiles is clearly visible. While only few differences occur for constant electricity prices, variable electricity prices more often allow identifying deviations. The higher electricity consumption in the low-price scenario results from to the comparatively low electricity price to the gas price ratio in this particular situation.

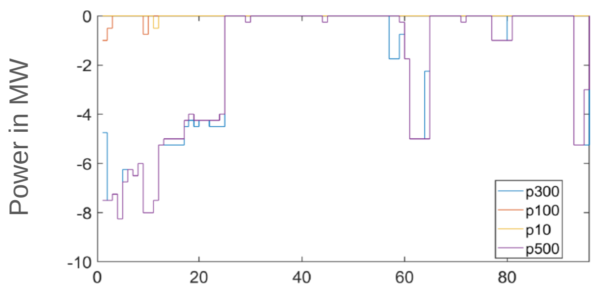

Figure 8: positive flexibility - variable low-price scenario

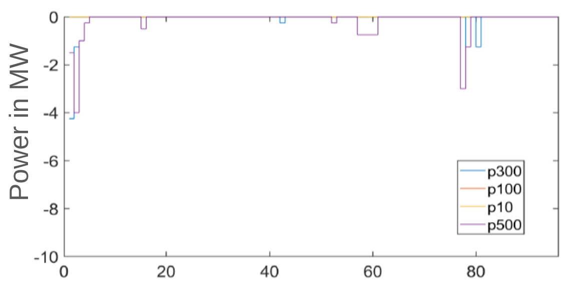

Figure 9: positive flexibility - constant low-price scenario

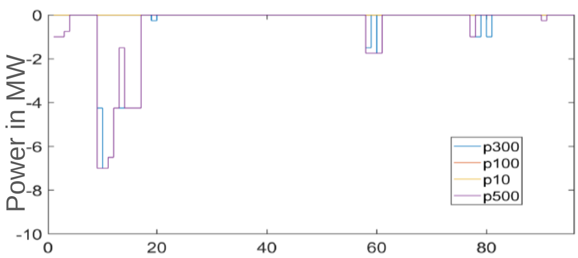

Figure 10: positive flexibility – variable high-price scenario

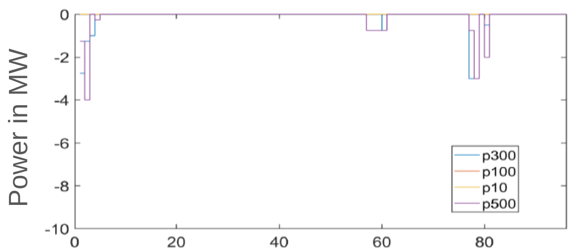

Figure 11: positive flexibility – constant high-price scenario

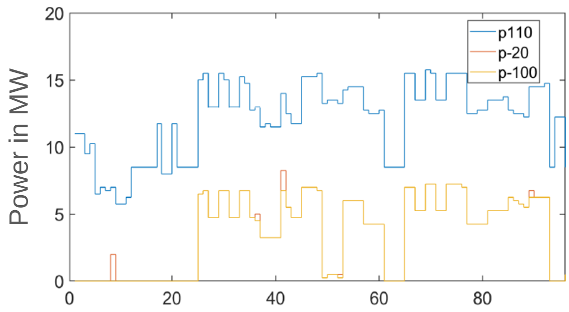

Figure 12: negative flexibility with variable base electricity price

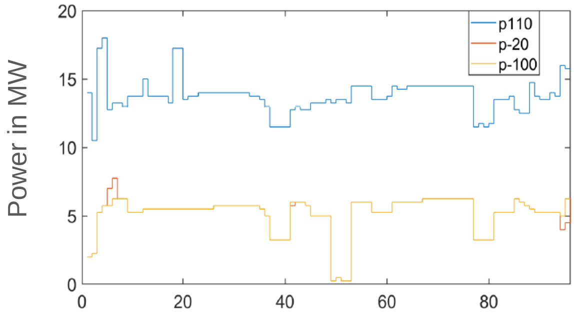

Figure 13: negative flexibility with constant base electricity price

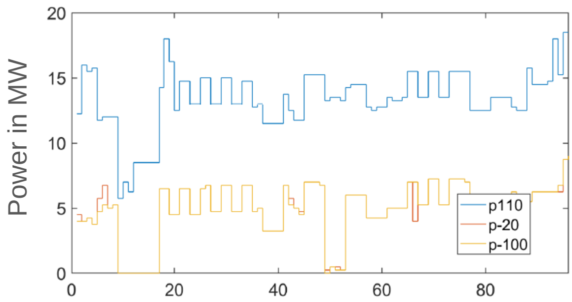

Figure 14: negative flexibility with variable base electricity price

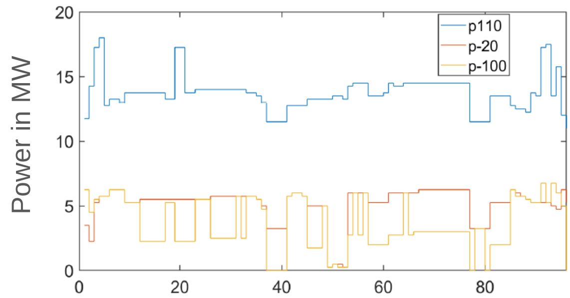

Figure 15: negative flexibility with constant base electricity price

Being both technically possible and economically viable, figures 8 to 15 show the identified flexibilities of power purchase in relation to the baseline. Significant differences can be obtained between the identified positive and negative flexibility potentials. The provision of negative flexibility (electricity consumption increase) has significantly higher potential compared to positive flexibility.

For positive flexibility, there are differences between different baseline scenarios. At constant electricity prices, only very low flexibility for very short timespans could be determined. Thus, these flexibilities are of limited use. In contrast, in the variable base electricity price scenarios, reasonable levels of positive flexible power in the range of 5MW could be detected for utilizable periods of time, but only with sufficiently high tariffs. Evidently an industrial company is rather an energy consumer with limited generation capacities. Thus, the potential for a further consumption reduction is technically restricted.

In contrast, great negative flexibility potential is perceived. Also, the differences with respect to the baseline scenarios are much smaller and occur only at individual points in time. A common pattern among all scenarios is the significant increase in flexible capacity at higher tariffs up to more than 12 MW. Moreover, it appears reasonable, that the industrial company may also offer flexibility to a level of about 5MW even at negative prices. This can be explained by the fact that the utilization of negative flexibility reduces the gas incurred for self-generation. However, these cases in particular represent a very efficient provision of flexibility, creating a very favorable business for both parties.

Detailed technical assessment: To provide a more comprehensive understanding from which components and operation modes the flexibility is obtained, a more detailed observation regarding the individual generation units and consuming processes is provided. The Figures 16 to 21 show the power supply units and power consumers for each of the two production sites. Initially, Figure 16 and 17 represent the baseline operation. In comparison,

Figure 18 to 21 present the divergent operation modes in case of positive and negative flexibility. They show that providing negative flexibility leads to reduction of the electricity production of the own turbines at both sites down to a technical minimum, so that the major portion can be procured from the power grid. Similarly, the generation of electricity from hydropower is reduced to a minimum within the allowable operating range. Evidently, the operation shows a completely opposite behavior in the case of positive flexibility. Electricity production by the steam turbines as well as hydro power operate at maximum capacity to minimize the residual load that needs to be covered by the power grid.

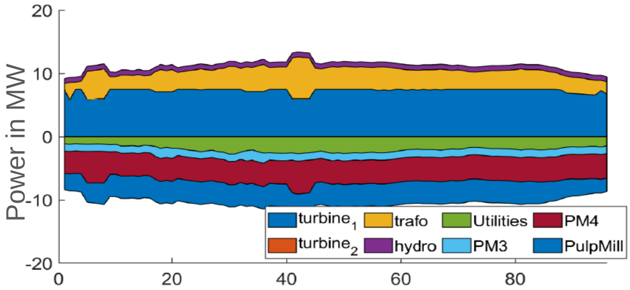

Figure 16: Baseline power balance production site 1

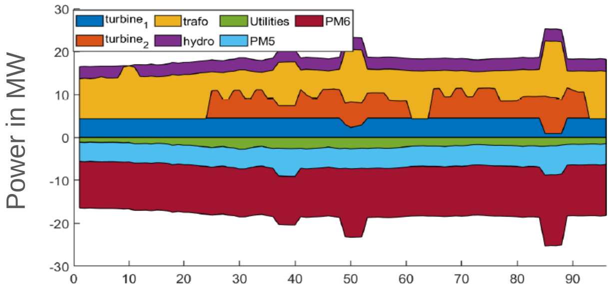

Figure 17: Baseline power balance production site 2

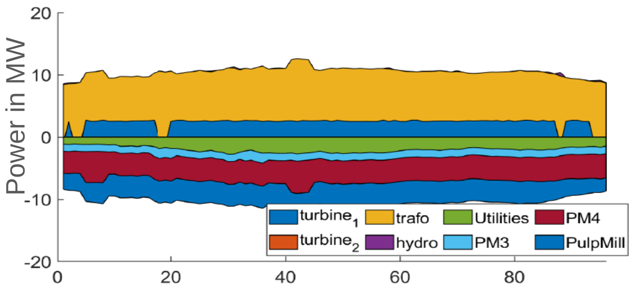

Figure 18: Negative flexibility power balance production site 1

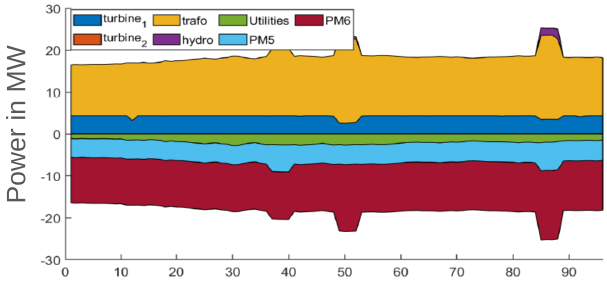

Figure 19: Negative flexibility power balance production site 2

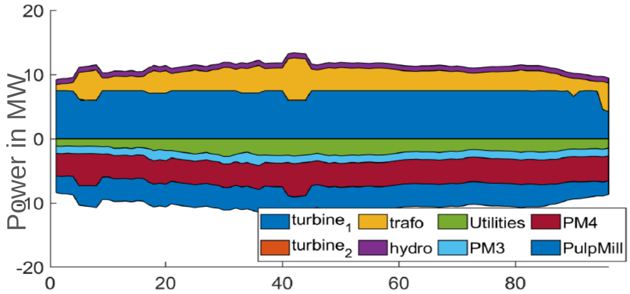

Figure 20: positive flexibility power balance production site 1

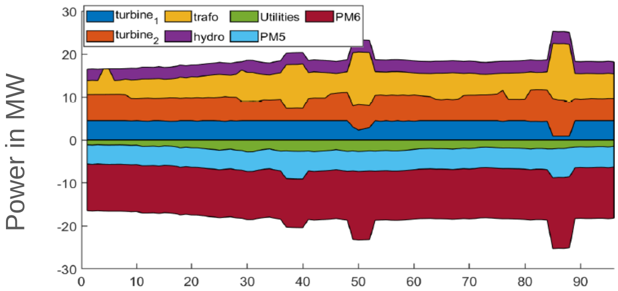

Figure 21: positive flexibility power balance production site 2

4 CONCLUSION

This paper provides a comprehensive insight into the operational perspective for evaluating the power consumption flexibility of industrial plants within their technical and economic framework. We showed a method to identify flexibilities to be marketed as ancillary services based on price assumptions for flexibility remuneration and the day ahead spot market price for the baseline power purchase. It becomes obvious that such flexibility identification is such a complex task, influenced by a wide range of parameters, that it necessitates the application of advanced mathematical methods. From a methodological point of view, this paper demonstrates, in particular looking at the overarching challenges of managing energy, the usefulness and versatility of mathematical optimization applications. The presented application allows a fast and uncomplicated model adaptation to different problems due to its modular modeling approach.

Considering the major outcomes, the variety of circumstances that influence the technical-economic flexibility in an industrial company is indicated. The baseline price and power price profile have a significant impact on the economics of flexibility. Observed large differences between positive and negative flexibility clearly relate to the plant setup and process restrictions. Evidently, such heat driven industrial companies are rather electricity consumers and the potential for a consumption increase is more suitable and beneficial than consumption reduction, even to such extent, that under certain conditions delivering negative flexibility at a negative price is economically possible. This could be a very efficient and favorable option in the management of high renewable penetration.

At this point, it needs to be stated, that the identified flexibilities must not to be misunderstood as actual revenues rather than a possible potential to profit by offering them at flexibility markets like the balancing power or energy service markets. Subsequently, this gives rise to the immediate problem of marketing the identified flexibilities in the most economical way. Considering the different timeframes and gate closure times of the respective markets, including their requirements, limitations and stochastic aspects, the necessity of the introduction of a more sophisticated bidding strategy is ultimately evident. In outlook to subsequent research work, such a bidding strategy is developed based on the presented method. It is integrated into a multi stage optimization algorithm using stochastic formulations to be able to consider both price and probability assumptions to an appropriate extent.

Acknowledgement

This work was supported by the project ”Industry4Redispatch”, which is part of the energy model region NEFI - New Energy for Industry and is funded by the Austrian Climate and Energy Fund [FFG, No.887780]. We particularly thank our industrial partner Mondi Neusiedler, who enabled the analysis of the pulp and paper production plants, provided the sufficient data and supported with operational information.

5 REFERENCES

[1] B. F. N. U. TOURISMUS, “#mission2030 - Die österreichische Klima- und Energiestrategie,” BUNDESMINISTERIUM FÜR VERKEHR, INNOVATION UND TECHNOLOGIE, Radetzkystraße 2, 1030 Wien, 2018.

[2] A. P. Grid, “APG,” [Online]. Available: https://www.apg.at/infografiken/. [Accessed 22 August 2022].

[3] Mohammadi M, Noorollahi Y, Mohammadi-ivatloo B, Yousefi H. Energy hub: From a model to a concept – A review. Renewable and Sustainable Energy Reviews 2017;80:1512–27. https://doi.org/10.1016/j.rser.2017.07.030.

[4] Morales-Espana, Latorre JM, Ramos A. Tight and Compact MILP Formulation for the Thermal Unit Commitment Problem. IEEE Trans Power Syst 2013;28:4897–908. https://doi.org/10.1109/TPWRS.2013.2251373.

[5] Halmschlager V, Birkelbach F, Hofmann R. Optimizing the utilization of excess heat for district heating in a chipboard production plant. Case Studies in Thermal Engineering 2021;25:100900. https://doi.org/10.1016/j.csite.2021.100900.

[6] Panuschka S, Hofmann R. Impact of thermal storage capacity, electricity and emission certificate costs on the optimal operation of an industrial energy system. Energy Conversion and Management 2019;185:622–35. https://doi.org/10.1016/j.enconman.2019.02.014.

II. Presentations: Industrial Waste Heat Utilisation

A TECHNO-ECONOMIC AND MACRO-ECONOMIC CONCEPT STUDY OF WASTE HEAT UTILIZATION OF A CEMENT PLANT

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Abstract: The utilization of waste heat between companies offers a possibility to reduce the total energy consumption, thus emitting less CO_2, reduce the dependency on gas imports, and saving costs. In this study, a techno-economic and macro-economic assessment in the course of high-temperature waste heat extraction, transportation and utilization from a cement plant to an industrial consumer is conducted. Based on price levels of February 2020, the results showed that economic viability can hardly be reached. CAPEX were evaluated for various process designs and range between €23 and €44 million. Fossil-fueled systems were too inexpensive in 2020 to compensate the high investment costs for utilizing an annually waste heat potential of 42-65 GWh (HHV). Subsidies and the integration of further demand (an increased amount of gas savings lead to increased cost savings) are essential to achieve positive economic viability (net present value). The macroeconomic analysis clearly shows positive effects on the gross regional product and employment through the domestic added value in the construction and avoidance of imports of fossil energy. The simulation revealed an average contribution of 6.2 million euros per year to the gross regional product and an increase in employment of approx. 80 employees in the first 10 years.

Keywords: industry; waste heat; thermal energy storage; economic feasibility; macroeconomics

Related project information:
This work was in course of the project Gmunden High Temperature Heat Link within the Energy Model Region "New Energy for Industry" (NEFI) funded by the Austrian Climate and Energy Fund (grant number 868854). Project partners are Technische Universität Wien, Energieinstitut an der Johannes Kepler Universität Linz, ste.p ZT GmbH, Energie AG Oberösterreich Vertrieb GmbH, Energie AG Oberösterreich Erzeugung GmbH, Kremsmüller Industrieanlagenbau KG, Zementwerk Hatschek GmbH und Porr Bau Gmb

1 INTRODUCTION

The utilization of waste heat between companies offers an opportunity for companies to reduce overall energy consumption. Thereby, less CO_2 is emitted, costs saved and the dependence on energy imports reduced. Existing implementations of industrial waste heat usage in Austria are elaborated in [1].

Cement is a very energy-intensive product. To produce one ton of cement, an energy of at least 1.6 GJ is theoretically required. However, according to [2], in industrial practice between 3 and 5 GJ are required to produce one ton of cement. This difference creates a large potential for waste heat utilization, with the waste gas exiting the rotary kiln having the greatest potential. The most commonly used ways to utilize waste heat from the cement plant include preheating of combustion air or materials, production of additional process steam in a waste heat steam generator, or energy conversion to electrical power using an ORC [2]. However, electricity generation only allows the utilization of the exergetic energy content of waste heat. The electricity generation efficiency is less than 30% [3]. In the case of direct energetic utilization of waste heat, it should be noted that the waste gas from the rotary kiln has a high dust load. This high dust load leads to a fouling process in the heat exchangers, the formation mechanisms of which have not yet been fully clarified [4]. The effects that the high dust load of the exhaust gas of a cement plant can have in a heat recovery steam generator, which is connected downstream of the rotary kiln, were described in detail by Leibinger [5]. The described steam generator, a two-pressure stage system installed for the first time in Europe in 2012 in the cement plant in Gmunden, operates on the basis of the Rankine process for the provision of electrical energy.

In the course of the Gmunden High Temperature Heat Link (GHTL) project, which is implemented in the NEFI (New Energy for Industry) showcase region as part of the Climate and Energy Fund's Energy Showcase, technical and non-technical aspects in the course of extraction, transport and utilization of high temperature waste heat from a cement plant to an industrial consumer is analysed. The objective of the research project GHTL is to develop and engineer a 10 MW_{th} high temperature heat recovery (at around 400°C) from a cement plant and to allow the transport of the heat to industrial customers (at around 200°C), which are more than 1.5 km away from the heat source (Figure 1).

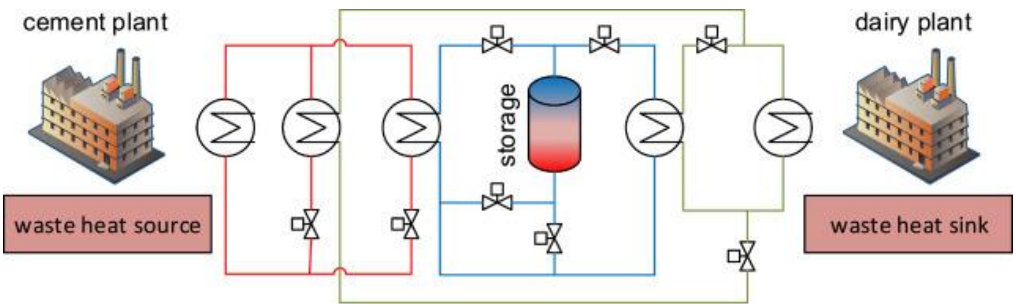

Figure 1: Flow sheet showing waste heat recovery (red), storage (blue), and transportation (green) based on [6, 7]

The project addresses innovative approaches on heat extraction, heat storage, heat transportation, and operation. For the heat extraction, the installation of a ceramic high temperature gas cleaning system combined with a finned tube heat exchanger was evaluated. The conventional way is to use plain tube heat exchangers. For the heat storage, a fixed-bed heat storage based on gravel (geocell) was built and tested on lab scale. Storage sizes of 6, 70, 330 and 5500 MWh were considered. For the transportation, pressurized water (45 bar, ~240°C), CO_2 (100 bar, ~350°C) and steam (10-25 bar, ~210-250°C) were considered.

The project is planned to be implemented in a subsequent KPC investment stage. Crossing public terrains with a heat transport piping at this temperature level has never been implemented before in Austria. The context calls for maximized standards of reliability and safety. Since the cement plant is subject to planned and unplanned process interruptions and production is shut down for two months in winter, a continuous supply of process heat to the customer cannot be guaranteed. Therefore, a thermal storage and/or back-up systems (gas boilers) are needed. A review of thermal storages and how to calculate maximum acceptable storage costs is conducted in [7].

2 MATERIAL AND METHODS

This section elaborates the analysed concepts in the course of the GHTL project. In addition, the main parameters and input data for the techno-economic and macro-economic assessment are described.

2.1 Description of Concepts

Almost 30 interconnections of the subsystems heat extraction fluid, storage system and district heating system were analyzed thermodynamically and with regard to the technical and economic optimum. A preliminary techno-economic feasibility study revealed that the concepts K0, K5, K9 and K10 are the most promising ones. Therefore, a detailed economic feasibility study was elaborated for those concepts. The concepts differ in the possible integration of a storage, storage size and different technical design options of the heat recovery, transportation and utilization.

Table 1: Description of developed concepts

K0	K5	K9	K10
• flue gas - steam loop • no storage • waste heat boiler (1-stage) with increased pressure as storage reserve, decreased waste heat potential • smooth-tube heat exchanger • 2 x shell boilers • emergency cooler • condensate collection, degasser, heat exchanger	• flue gas-steam-(salt)-steam loop • Ruth-storage $6MWh_{th}$ • waste heat boiler (2-stage), incrased waste heat recovery • smooth-tube heat exchanger • steam mixture from superheater 1 and 2 • 2 x shell boilers • emergency cooler • condensate collection, degasser, heat exchanger	• flue gas-steam-air loop • storage $330MWh_{th}$ • special waste heat boiler (1-stage) • finnedtube heat exchanger (air) • maximized waste heat usage • 2 x shell boilers • emergency cooler • condensate collection, degasser, heat exchanger	• flue gas-steam/water loop • pressurized hot water storage $6MWh_{th}$ • steam generator • waste heat boiler (1-stage) • smooth-tube heat exchanger • 2 x shell boilers • emergency cooler • condensate collection, degasser, heat exchanger

2.2 Development of techno-economic assessment tool

A techno-economic assessment tool is modelled by *Energieinstitut an der JKU Linz*. The tool uses several factors to proof the economic viability of each concept, which are listed in Table 2. Service and maintenance work (OPEX) are considered annually with 2% of the investment cost. CAPEX are evaluated with the price level of February 2020. Reinvestments are not considered. A possible subsidy of the investment cost is taken entirely into account in the investment year (t=0).

Table 2: Required input parameters for techno-economic assessment

Parameter	value	unit	remarks
Gas network costs	2.4	€/MWh	Based on HHV, based on regulation
Gas price	25	€/MWh	Based on HHV, determined within consortium
Costs of gas and network	27.4	€/MWh	Sum of gas network costs and gas price, but does not include taxes and duties
Subsidy for investment costs	30	%	Estimated amount of KPC subsidy, without considering the cap of 4.5 Mio €, subsidy is taken into account in investment year (t=0)
Cost calculation interest rate	6	%	Determined within consortium
Cost calculation period	10	a	Determined within consortium
CO_2 emission savings	0.24	t/MWh	Derived from KPC subsidy guidelines and Umweltbundesamt CO_2eq, based on HHV
CO_2 emission allowance price	varied	€/t	Impact is shown via a sensitivity analysis
storage size	selectable	MWh	Sizes: 4-6, 70, 330, 5500 MWh
saved energy through storage	Based on selected storage size	GWh	Based on HHV, energy saved through peak shaving and valley filling via storage
price change factor operational costs	1	-	Not applied
price change factor savings	1	-	Not applied
annuity factor	0.136	-	Applying a 6% interest rate and a calculation period of 10 years
Investment costs scenario	please choose (drop down menu)	-	K0 Basis, K5 Basis, K9 Basis, K10 Basis, K0_AC, K5_AC, K9_AC, K10_AC
Input energy consumption for calculation	Based on selected scenario	GWh	Based on HHV
Investment costs (CAPEX)	Based on selected scenario	€	Input from CAPEX evaluation
Maintenance/Service (OPEX)	2	%	Assumption: 2% per year of investment cost
Calculated Maintenance/Service	Based on selected scenario	€	Calculated value
waste heat potential	Based on selected scenario	GWh	Based on HHV, extracted waste heat potential from cement plant
unused waste heat potential	Based on selected scenario	GWh	Based on HHV

Based on the selected input parameters, the techno-economic assessment tool calculates the net present value (NPV), the LCOH (levelized costs of heat), the amortization period (static and dynamic), the static and dynamic return on investment (ROI), the internal rate of return (IRR) and the annuity. The annuity method includes capital, demand und operation-related costs as well as the annuity of proceeds and other additional costs.

The key parameters for the techno-economic assessment are the gas price, the energy consumption, potential subsidies, potential CO_2 emission allowances, the calculation period and the interest rate. The mentioned economic parameters are calculated for each concept.

To provide insights on the impact of potential subsidies and CO_2 prices, the results of each concept are calculated based on following sub scenarios:

1) “Results basis” (without a subsidy, no CO_2 emission allowance price)
2) Results including a 30% subsidy on the CAPEX, but no CO_2 emission allowance price
3) Results including a 30% subsidy on the CAPEX and a CO_2 emission allowance price of 50 €/t

A sensitivity analysis is conducted to show the impact of gas price, the energy consumption, potential subsidies, potential CO_2 emission allowances, the calculation period and the interest rate. Sensitivity results are structured in:

a) The sensitivity analysis tests for uncertainties, which include the main customer’s energy demand, gas price fluctuations, CO_2 emission allowance prices or potential subsidies. The sensitivity was shown for:
b) NPV in dependence of gas price and energy consumption
c) NPV in dependence of gas price, energy consumption and subsidies
d) NPV in dependence of gas price, energy consumption, subsidies and CO_2 emission allowances of 50 €/t
e) NPV in dependence of energy consumption and CO_2 emission allowances
f) Annuity including subsidies and in dependence of calculation period and interest rate
g) Impact by changing following parameters on annuity (CAPEX, OPEX, savings/year, energy consumption)
h) Max CAPEX in dependence of energy consumption and calculation period

2.3 Macro-economic assessment

The macroeconomic simulation uses the *Energieinstitut an der JKU Linz* in-house tool MOVE2. MOVE2 is designed for detailed macroeconomic impact analyses of (economic, energy policy and structural) changes as well as changes in the energy market in Upper Austria. In comparison to the techno-economic analyses, the focus is not on the micro level (end consumers, companies), but on the entire economy of the Austrian state of Upper Austria. In particular, the focus is on investment impulses resulting from the construction of the required infrastructure (recovery, pipeline, heat transmission and additional expenditures for demand-side integration) and regional trade balance effects resulting from the substitution of imported natural gas by the usage of waste heat.

MOVE2 uses the cost parameters and results from the techno-economic analysis of concept K0 as essential inputs. In order to display the explicit effects of policy measures and investment decisions, two scenarios are set up in the MOVE2 model for simulations. First, a baseline scenario of developments in the Upper Austrian economy is calibrated by historical data. Second, a scenario is modeled, which involves a projection of what will happen due to the inter-company waste heat cooperation envisaged in the GHTL project. By subtracting the simulation results of the cooperation-scenario from the baseline scenario, it becomes possible to identify and characterize the exact additional macroeconomic impacts. In summary, the simulations via MOVE2 illustrate the difference between what will happen if everything stays constant and what will happen in case of the cooperation through heat recovery and its redirection to industrial consumers.

The simulation is based on several assumptions:

- Simulation horizon of 11 years (t=0…10)
- Geographical reference: Upper Austria
- Value added shares and import quotas were assumed for the technologies and components considered within the project
- Investments' effectiveness and financing are considered

3 RESULTS

In this section, some key results of the techno-economic assessment and macro-economic assessment are described. Detailed results are confidential and cannot be provided.

3.1 Techno-economic assessment

The investment costs (CAPEX) for the concepts were evaluated by the company partner Kremsmüller with the support of the GHTL project team. In a first step, the initial CAPEX for concept K0 were elaborated in more detail, based on several discussions, tenders, the experience of the project team and especially based on the engineering expertise of project partner Kremsmüller. In a second step, and based on the CAPEX elaboration of K0, the CAPEX for the concepts K5, K9 and K10 were derived using cost calculation factors (e.g., factors based on the methods by Lang, Weber, Peters, etc.) and the knowledge and experience of project partners in their specific business fields.

The analysis of the waste heat potential revealed that there is still waste heat available after supplying the proposed industrial consumer (dairy). Therefore, each basis concept (K0, K5, K9 and K10) was extended by assuming that there are additional customers (AC) in order to substitute additional gas costs. The CAPEX for the concepts with additional customers were determined too. The slightly increased investment costs due to the connection of additional customers are offset by further gas savings of between 9 and 11 GWh (HHV) depending on the concept.

Concept K0 does not include a storage; therefore, it is the least investment cost concept with investment costs of approx. €23 million. Annual gas savings are approx. 42 GWh (HHV). In addition to technical changes to the heat recovery system, concepts K5 and K10 include a 6 MWh_{th} storage, which leads to increased investment cost. However, this also increases the gas savings and thus saves more costs. In the K9 concept, a 330 MWh_{th} storage is included. This storage can be designed vertically or horizontally, and in each case in a single or dual modular design (1x 330 MWh_{th} or 2x 165 MWh_{th}, respectively). The investment costs of K9 is around €44 million, which makes it the most cost-intensive concept. However, this concept also leads to the highest gas savings of around 54 GWh (HHV).

The least-cost concept K0 shows a negative NPV. It could be increased by an investment subsidy of 30% and an additional CO_2 tax of 50 €/t, but would be still negative. If additional customers are considered, the calculation including subsidy and CO_2 taxation still shows a negative NPV. The main factors influencing profitability are CO_2 tax, costs of gas and network, investment costs and subsidies.

The economic assessment of the most cost-intensive concept K9 results also in a negative NPV. Again, the main factors for this concept influencing profitability are CO_2 tax, costs of gas and network, investment costs and subsidies.

3.2 Macro-economic assessment

The simulation results of the economic effects of the recovery, transmission and utilization of waste heat (as potentially implemented by the project) indicate a positive macroeconomic benefit in the form of an increase in gross regional product and employment. The detailed results of the macroeconomic simulation are confidential. However, the positive developments are mainly based on

1) additional investment impulses in the first year (t=0) as a result of the investment, i.e., the implementation of the recovery and heat exchange technologies as well as the pipeline and necessary construction and engineering;
2) positive effects on the regional trade balance (net exports) due to the decrease of fossil energy imports (natural gas) for heat production during the recovery, storage and utilization of waste heat (t=1,...,10), which exceed the value added outflows due to the investments in the initial year (t=0);
3) multi-round effects from 1) to 2).

Compared to a situation without the recovery, transmission and utilization of waste heat achieved through the GHTL concept, the macro-econometric simulation analysis shows an increase of the gross regional product by approx. 19.2 million € in the initial year (t=0) and by 2.7 million € after an operation phase of 10 years (t=10). This corresponds to an average increase of about € 6.2 million € in the gross regional product per year in Upper Austria over the entire period (Table 3). The drivers of the additional value added are, additional to the investment impulses in the initial year (t=0), the substitution of natural gas imports. This results in positive effects on the trade balance amounting to an average of approx. 1.7 million € per year in the period of recovery, transmission and use of the waste heat (t=1,...,10). The most significant employment effects in the form of additional approx. 220 employees are recorded in the initial year (t=0) as a result of the investment activities.

Table 3: Macroeconomic and ecologic effects in Upper Austria through the recovery, transmission and utilization of waste heat by industrial consumers (Source: Own calculations based on the simulation model MOVE2, Linz, July 2021)

	GRP	**Investments** of companies	**Consumption** of private households	**Net exports**	**Employment**	**CO_2e emissions**
Point of time	*million €*	*million €*	*million €*	*million €*	*employees*	*tons*
t = 0	**+ 19.2**	**+ 19.1**	**+ 4.8**	**- 4.7**	**+ 220**	**+ 1.718**
t = 1	+ 10.5	+ 2.8	+ 2.9	+ 4.8	+ 170	- 10.100
t = 2	+ 7.6	+ 1.5	+ 3.0	+ 3.1	+ 130	- 10.230
t = 3	+ 5.8	+ 1.0	+ 2.2	+ 2.6	+ 100	- 10.780
t = 4	+ 4.9	+ 0.7	+ 2.0	+ 2.2	+ 80	- 10.860
t = 5	+ 4.3	+ 0.6	+ 1.7	+ 2.1	+ 60	- 10.910
t = 6	+ 3.9	+ 0.5	+ 1.5	+ 2.0	+ 50	- 10.950
t = 7	+ 3.5	+ 0.4	+ 1.3	+ 1.9	+ 30	- 10.980
t = 8	+ 3.2	+ 0.3	+ 1.1	+ 1.8	+ 30	- 11.010

t = 9	+ 3.0	+ 0.3	+ 0.9	+ 1.8	+ 20	- 11.040
t = 10	+ 2.7	+ 0.2	+ 0.8	+ 1.7	+ 10	- 11.070
Ø t = 1,...,10 Heat recovery, transmission and utilization	**+ 4.9**	**+ 0.8**	**+ 1.7**	**+ 2.4**	**+ 70**	**- 9.660**
Ø t = 0,...,10 Implementation / Construction + Heat recovery, transmission and utilization	**+ 6.2**	**+ 2.5**	**+ 2.0**	**+ 1.7**	**+ 80**	**- 10.790**

4 DISCUSSION

The available waste heat of 70 to 90 GWh (depending on the concept) would have a theoretical CO_2 emission avoidance potential of up to 22,000 tons (22kt) of CO_2 per year. The analyzed concepts with operational storage (K5 and K10), with day storage (K9), or without storage (K0) allow waste heat to be used in the range of 42 GWh annually to 65 GWh annually (47 to 72% of the maximum potential). The energy saved and thus the cost savings from the use of waste heat are low. Economic viability can therefore hardly be achieved, since high investment costs are required for heat recovery from the dusty flue gases of the cement plant. Established fossil-fueled systems were still too inexpensive in 2020. Subsidies and an increased use of waste heat as process heat (a higher amount of gas savings leads to higher cost savings) are essential for a positive economic return (net present value). Geopolitical events in Europe 2021/2022 dramatically increased gas prices (Figure 2), which, of course, has a positive impact on the financial viability of the GHTL project. In August 2022, gas prices were up to 230 €/MWh. With such high gas prices, economic viability could definitely be achieved. However, the future development of gas prices is hardly predictable.

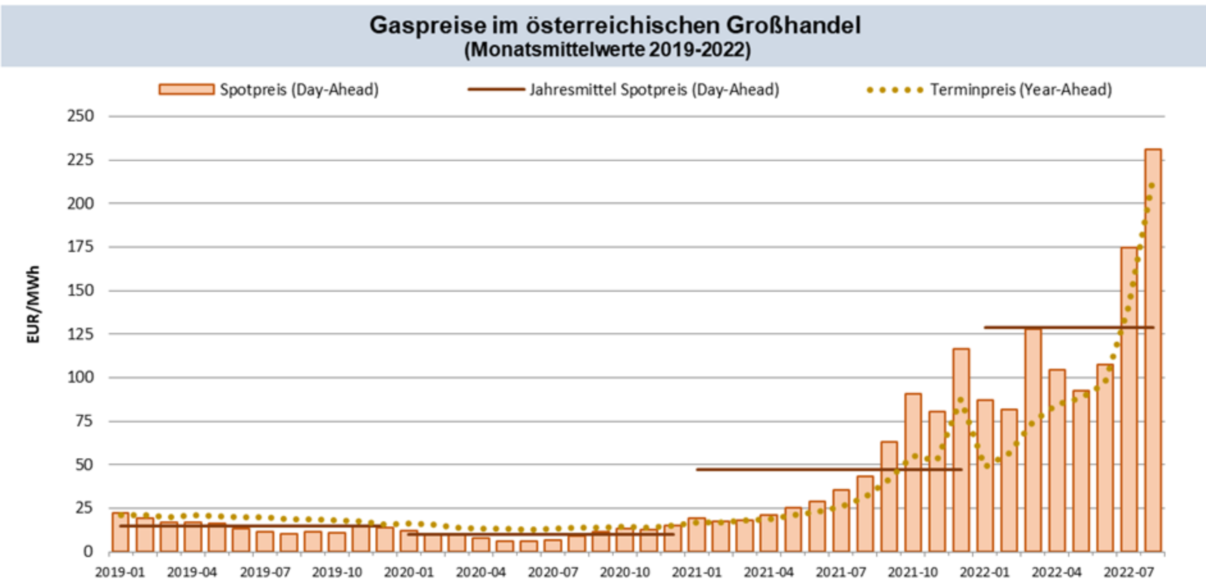

Figure 2: Gas price development in Austria from 2019/01 to 2022/08. Source: E-Control

The following key data are the essential input variables for the profitability of the project:

- investment costs
- running costs (operating costs)
- economic observation period (useful life)
- interest rate

- spec. fuel costs
- substituted amount of primary energy
- funding (especially Invest funding)
- other costs avoided (e.g. taxes per kWh or per ton of CO_2) based on the amount of primary energy and emissions avoided.

To get a better understanding and overview of the required CO_2 taxation from the evaluated concepts, Figure 3 provides an overview of the CO_2 taxation in the European Union. The applied CO_2 taxation varies significantly between the different states and can go up to 135 €/t. The CO_2 taxes are listed in $€_{2020}$ per ton of CO_2e outside the EU ETS.

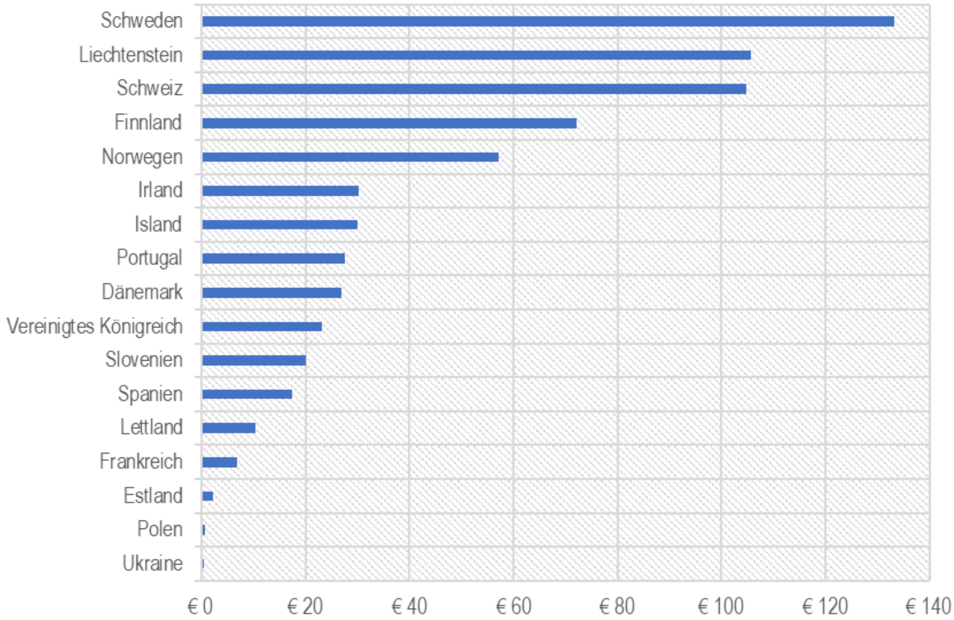

Figure 3: CO2 taxes (in €2020 per tonne CO2e) outside the EU ETS in European countries - as of 2020. Source: Own illustration based on data from the World Bank - Carbon Pricing Dashboard.

Due to the temperatures of more than 200°C, the project is breaking new legal ground. The district heating exemption regulation only applies up to a maximum of 180°C. It can be deduced that the stated legal requirements must be complied with and approvals and permits obtained. However, these aspects are common procedures and in no way represent legal restrictions that speak against the implementation of high-temperature process heat conduction per se.

5 CONCLUSION

On the basis of the key data currently applicable to the GHTL project, it was unfortunately not possible to demonstrate an economic feasibility for any of the examined waste heat utilization concepts. For concepts implementing larger heat storage systems, the economic viability deteriorated under the prevailing framework conditions of 2020. The saved energy of around 40 to 60 GWh yearly and thus cost savings through utilizing the waste heat is too low to compensate the high investment costs. Fossil driven systems were still too inexpensive in 2020. Changes on legal, funding, political, etc. levels are needed to make such enormous waste heat potential economically viable. Due to geopolitical incidents in Europe in 2021/2022, gas prices have risen to a level that could not be predicted and calculated even with sensitivity analyses. High gas prices naturally have a positive effect on the GHTL project's financial viability. With gas price levels of August 2022, economic viability could definitely be achieved. In addition, waste heat utilization reduces the dependence and import of fossil fuels.

A clear macro-economic added value can be derived. The simulation results in an average contribution of 6.2 million euros per year to the gross regional product and an increase in employment of approx. 80 employees in the first 10 years.

6 REFERENCES

[1] S. Moser and S. Lassacher, “External use of industrial waste heat - An analysis of existing implementations in Austria,” *Journal of Cleaner Production,* vol. 264, no. https://doi.org/10.1016/j.jclepro.2020.121531, 2020.

[2] A. Amiri and M. R. Vaseghi, “Waste Heat Recovery Power Generation Systems for Cement,” *IEEE Transactions on Industry Applications,* vol. 51, pp. 13-19, 2015.

[3] S. Karellas, A.-D. Leontaritis, G. Panousis, E. Bellos and E. Kakaras, “Energetic and exergetic analysis of waste heat recovery systems in the cement industry,” *Energy,* vol. 58, no. https://doi.org/10.1016/j.energy.2013.03.097, 2013.

[4] M.-J. Li, S.-Z. Tang, F.-L. Wang, Q.-X. Zhao and W.-Q. Tao, “Gas-side fouling, erosion and corrosion of heat exchangers for middle/low temperature waste heat utilization: A review on simulation and experiment,” *Applied Thermal Engineering,* vol. 126, no. https://doi.org/10.1016/j.applthermaleng.2017.07.095, 2017.

[5] H. Leibinger, “Stromerzeugung aus der Abgaswärme durch ein Abhitze-Dampfkraftwerk im Zementwerk Rohrdorf,“,” *Kraftwerkstechnik - Sichere und Nachhaltige Energieversorgung,* vol. 5, 2013.

[6] M. Haider, “ Projekt Zwischenstatus: Gmunden High Temperature Heat Link,” no. https://nachhaltigwirtschaften.at/resources/nw_pdf/events/20191009_highlights/haider_nefi-gmunden.pdf, 2019.

[7] S. Puschnigg, J. Lindorfer, S. Moser and T. Kienberger, “Techno-economic aspects of increasing primary energy efficiency in industrial branches using thermal energy storage,” *Journal of Energy Storage,* vol. 36, no. https://doi.org/10.1016/j.est.2021.102344, 2021.

ASSESSMENT OF THE FUTURE WASTE HEAT POTENTIAL FROM ELECTROLYSERS AND ITS UTILIZATION IN DISTRICT HEATING

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Abstract: Hydrogen will play a significant role in the decarbonization of an integrated energy system, i.e. the European Hydrogen Strategy sets the ambitious goals of the production of 10 Mio. tons of green H_2 by 2030. The International Energy Agency expects a hydrogen demand of up to 530 Mt in 2050. However, to foster the transition to a smart energy system, synergies within the energy systems need to be utilized. Especially for increasing the overall system efficiency, the generated waste heat of electrolysers will need to be considered. This can amount to a significant potential for providing heat to e.g. low-temperature processes, offices, service buildings, or residential applications, either directly or via a district heating network. The focus of this paper is the assessment of the potential of waste heat from electrolysers on a national level in Europe and worldwide, based on scenarios for their expected capacities and key technology performance data. Further on, a comparison of the waste heat potential and the projected final heat demand supplied by district heating networks has been done.

Keywords: Hydrogen; waste heat; utilization; district heating, potential assessment

1 INTRODUCTION

It is commonly agreed upon that hydrogen will play a significant role in the decarbonization of an integrated energy system as the link between previously separated sectors of power, gas, mobility, industry and households. Currently, hydrogen is mostly used as feedstock for industrial processes and predominantly produced from natural gas with steam reforming. The global hydrogen demand was at 90 Mt H_2 in 2020, stemming from refineries, the chemical industry and steelmaking processes. Globally installed electrolysis capacities were at 290 MW in 2020, producing 30 kt H_2 corresponding only to 0.03% of the overall production [1]. The installed capacity is expected to increase significantly in the next decade with estimations ranging from 25 GW [2] to 90 GW [3] by the year 2030. The European Hydrogen Strategy [4], adopted in July 2020, sets the ambitious goals of the construction of 40 GW electrolyser capacity and the production of 10 Mio. tons of green H_2 by 2030. The International Energy Agency expects in their Net-Zero Emissions scenario a hydrogen demand of up to 530 Mt in 2050 [1].

While currently the production of H_2 predominantly takes place in temporal and spatial coherence with the demand, that coherence will change with increasing production and demand volumes of green hydrogen. The production of green hydrogen will shift from the demand centers to the generation sites of renewable electricity. Here, large-scale electrolyser capacities are expected to emerge, producing hydrogen that is then transported to the off-takers.

To foster the transition to a smart energy system, synergies within the energy systems need be utilized. By positioning the electrolysers in proximity to the renewable electricity generators, capacity constraints of the electrical grid can be circumvented. Additionally, for increasing the overall system efficiency, the generated waste heat of electrolysers will need to be considered, as it amounts to a significant potential for providing heat to e.g. low temperature processes, offices, service buildings or residential applications, either directly or via a district heating network [5].

The focus of this paper is the assessment of the potential of waste heat from electrolysers on a national level in Europe and worldwide. Further on, a comparison of the waste heat potential and the projected final heat demand supplied by district heating networks has been done.

2 SOURCES FOR WASTE HEAT FROM ELECTROLYSIS PROCESSES

The production of hydrogen from water and renewable electricity with electrolysers is the preferred production path in the future. There is a multitude of different technologies available at varying technology readiness levels. However, three electrolyser types constitute the most relevant technologies [6]: Alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEM-EL) and solid oxide electrolysis (SOEL). As these technologies operate at different temperatures and with different efficiencies, the waste heat potential is assessed for each technology individually. An overview of the key parameters for the technologies is given in Table 1.

Table 1 KPIs of electrolysis technologies, based on [2], [6]–[9]

	AEL	PEM-EL	SOEL
TRL	9	8 - 9	6 - 7
Operating temperature [°C]	60 - 90	50 - 80	650 - 900
Electric efficiency (LHV)	50 - 71	50 - 68	75 - 85
Recoverable waste heat (% of electricity input)	16 - 30	20 - 30	-
Waste heat temperature [°C]	50 - 80	1 - 80	-

2.1 Alkaline electrolysis

Alkaline electrolysis is the most mature water electrolysis technology with multiple commercial installations in the MW range [10]. Similar to PEM electrolysis the operating temperature is below 100°C, allowing liquid water as input for the process. Benefits of this technology are the low capital costs, high lifetime of the components and the availability. On the contrary, disadvantages are the limited operating pressure, resulting in higher costs for subsequent compression of the produced hydrogen, low current densities and limited flexibility for dynamic operation [6]. Considering the availability of waste heat, literature values imply that 16% of the electricity input can be recovered at a temperature of 50°C. By 2024, the temperature of the available waste heat is expected to increase to 70°C [8]. Different sources indicate a waste heat share of 20% – 30% in a temperature range of 60°C – 80°C [9].

2.2 PEM electrolysis

PEM electrolysis is seen as one of the most promising solutions for efficient hydrogen production from renewable energy sources and has already reached a commercial level. The compact design, the high current density and efficiency, the low operating temperature (50-80°C) and the possibility of a flexible operation (fast cold start-up times) make it an attractive solution [10]. Due to the usage of expensive catalysts and limited production capacities, capital costs for PEM-EL are higher than for AEL. Additionally, the stack of current systems has a limited lifetime, resulting in additional expenses when replacement is needed [6]. Similar to AEL, literature values imply a waste heat share of 20% – 30% in a temperature range of 60°C – 80°C [9], while a different source states that heat can be recovered at a temperature of 50°C (expected to increase to 70°C by 2024). The available share of waste heat is expected to reach values of 26% of the electricity input [8].

2.3 SOEL

Contrary to the other two technologies, SOEL is operating at high temperatures (650 – 900°C) and with the input of steam. While the overall energy demand of splitting water in hydrogen and oxygen is increasing slightly with increasing temperature, the electricity demand is decreasing as more heat is utilized [11]. Therefore, high electrical efficiencies in the range of 81 – 86% (lower heating value) can be achieved with SOEL [6]. Existing challenges with this technology are material degradation due to the high operating temperature and limited flexible operation due to the long start up times [11]. Whereas the other electrolysis technologies are generating waste heat that can be utilized, SOEL is relying on an external heat input. A possibility to provide the thermal energy input is industrial waste heat: The European project "GrInHy2.0" is demonstrating the implementation of a high-temperature SOE plant in an integrated steel production facility, utilizing waste heat from the steel making processes as heat input to the SOE. With this configuration, hydrogen is produced with electrical efficiencies of 84% (considering the lower heating value) [12].

2.4 Examples of the utilization of the waste heat

Promising utilization options for the integration of waste heat from electrolysers are the supply to a nearby district heating network or the supply to industrial processes. Following demonstration projects can be summarized:

MPREIS Hydrogen: The Austrian supermarket chain MPREIS is generating green hydrogen in their headquarter in Völs, Tyrol. The 3.2 MW plant is currently the largest single-stack electrolyser in Europe. Alkaline pressure electrolysis is the chosen technology for the generation. The generated hydrogen is used in their bakeries and as fuel for their own truck fleet. The waste heat is reused in their production processes. 70% of the input electricity is converted to hydrogen while about two thirds of the heat losses are reused [13].

Pilot project „Power to Gas" Ibbenbüren: In the city of Ibbenbüren, Germany, a plant for hydrogen production by PEM electrolysis with a rated power of 150 kW is being tested since 2015. The aim of the test is to proof the functionality of an electrolyser in interaction with the fluctuating electricity production from renewables under real-life conditions. This plant is the first one in Germany with a multiple waste heat utilization at a temperature of around 56°C. The overall efficiency of the system is at 86% [14] [15].

WindGas Falkenhagen: In Falkenhagen, Germany, Uniper has built a demonstration plant for the generation of green hydrogen by alkaline electrolysis fed by wind power. The 2 MW plant is in operation since May 2018. The hydrogen is supplied to a high-pressure natural gas grid. The heat from the process is used in an adjoining veneer factory. [16] [17]

Green Hydrogen Esslingen: For a newly developed city quarter with a size of 120,000 m², a climate-neural energy concept was developed that includes the production and use of green hydrogen. The 1 MW electrolyser, capable of producing 400 kg of hydrogen per day, is powered by excess electricity from the rooftop PV installations and a nearby wind turbine. The hydrogen is used for different applications: feed-in into the local gas grid, mobility applications and for the generation of electricity in times of low renewable production. The waste heat of the electrolyser is utilized for heating the quarter, raising the overall efficiency of the system to around 90% [18].

H-Flex project Nieuwegein: Within the H-Flex project, a 2.5 MW PEM electrolyser is planned in the City of Nieuwegein to supply 250 t of hydrogen per year for a hydrogen refueling station. The system generates waste heat at a temperature of 62°C that can be used in an adjacent laundry. A detailed techno-economic analysis of the use case revealed that 1,720 MWh of heat can be delivered to the customer at 54°C, resulting in annual costs savings of 65,000 € and CO_2 savings of 480 t due to reduced natural gas consumption. With the heat utilization, the overall efficiency of the system increase to 91% [19].

3 IDENTIFICATION OF WASTE HEAT POTENTIALS

3.1 Selected potential analyses and studies

In the past, the utilization of waste heat on an urban or country scale has been addressed in different studies:

The future hydrogen plants in the Rotterdam port: The study estimated that the future hydrogen plants in the Rotterdam port industrial area will be able to provide the equivalent of around 500,000 households with heat by 2030. By 2050, the number of supplied households could even rise to around one million [20].

Integration of waste heat in the district heating network in Luleå, Sweden: The study showed that 203 GWh_{th} can be extracted from a PEM electrolyser (100 MW) with a waste heat temperature of 79°C, while 171 GWh_{th} can be integrated in the DH network annually. For an alkaline electrolyser, 310 GWh_{th} can be extracted at a waste heat temperature of 80°C, while 226 GWh_{th} can be integrated in the DH annually. The overall system efficiency is 94.7 % and 88.4 % for PEM and alkaline systems, respectively [21].

Waste-heat utilization potential in a hydrogen-based energy system - An exploratory focus on Italy: The study estimated that in a hydrogen-based energy system a potential of more than 30 TWh of high temperature waste heat (mainly from the synthesis of hydrogen derivates) and low temperature waste heat (from PEM electrolysis) can be generated by 2050. The sum of theses potentials corresponds roughly to a quarter of the total heat demand in civil sector for space heating and domestic hot water [22].

Heat Roadmap Europe 4: The aim of this study was to derive scenarios for the decarbonization of the European heating and cooling market by 2050. In doing so, 14 countries were considered, which account for over 90% of the European heating and cooling demand.

In the main scenario, 155 TWh of waste heat from electrolysers and electrofuel plants (e.g., methanation generating additional waste heat) can be integrate into the DH sector, covering 14% of the total DH supply [23].

3.2 Evaluation of the potential in Europe

Due to the low market penetration of electrolyser technology today, it is difficult to obtain comprehensive data regarding their location and sizes. Most of the current installations are still demonstration projects that are not suited for the utilization of waste heat from the production. Additionally, gathering localized data on these installations is challenging and was not possible in a satisfactory quality within this project. Therefore, the waste heat potential of electrolysers is assessed based on scenarios for their expected capacities by the years 2030 and 2040. On a European level, an assessment of the installed electrolyser capacity for the production of hydrogen and synthetic fuels is available on a national level from the scenarios of the TYNDP 2022 [24]. In these scenarios, the electrolysis capacity in the EU27 + UK reaches 70 GW and 272 GW by the years 2030 and 2040, respectively. The data from the TYNDP 2022 is combined with data on the global installed capacity from the Net-Zero Emissions scenario from the IEA, assuming capacities of 850 GW and 2,440 GW by 2030 and 2040, respectively [25]. To analyze the waste heat potential, assumptions on the technology share, full load hours and waste heat share are required.

Challenging for the utilization of waste heat from electrolysers is their operation schedule. As bulk hydrogen production (running 8760 h/year) is generally not viable due to high electricity spot prices, flexible operation is expected to be the best approach. With increasing shares of renewables in the energy system, electricity prices will be low in times of high feed in from wind and solar. Production of hydrogen will therefore follow the availability of renewable electricity [2]. A graphic representation of this is given in Figure 1. If electricity prices are over a certain threshold, the electrolyser cannot operate economically feasible and is shut down.

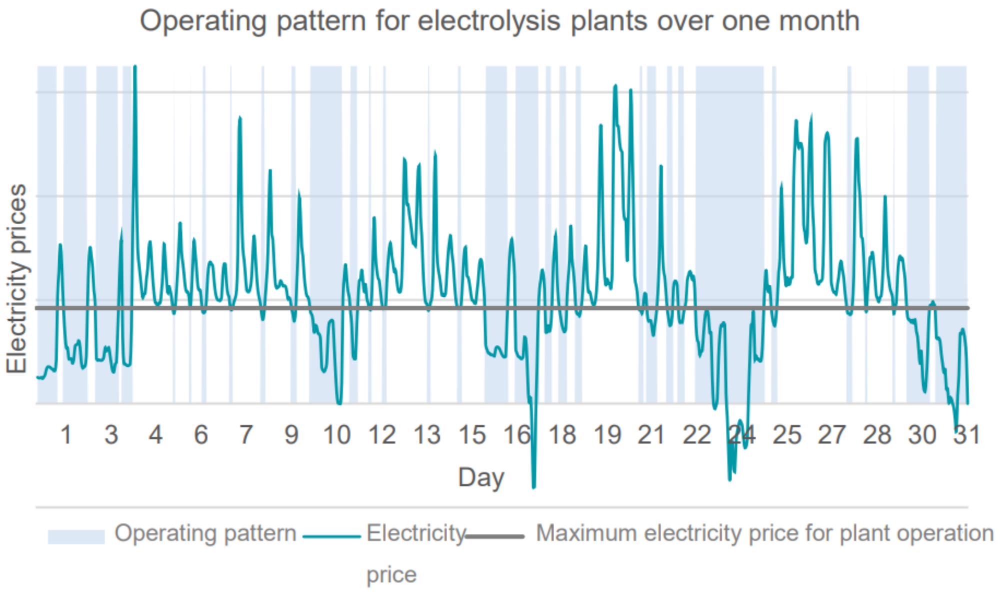

Figure 1: Example operation schedule of a grid connected electrolyser depending on the electricity prices [26].

The IEA calculated the current production cost of hydrogen from water electrolysis and derived the optimum level of full load hours to be in the range of 3,000 to 6,000. With increasing full load hours, the impact of capital costs for the electrolyser becomes less relevant and electricity prices are the determine cost component [25]. Böhm et al. assumed a cost optimized operation at 3,500 full load hours [27].

The chosen parameters for the assessment are summarized in Table 2.

Table 2: Parameters for the calculation of the waste heat potential of electrolysers [7]–[9], [25], [27], [28].

	Waste heat share, WHS	Waste heat temperature	Technology share, TS		Full load hours, FLH
			2030	2040	
AEL	20%	70°C	80%	52%	3,500
PEM-EL	25%	70°C	18%	40%	3,500
SOEL	-	-	2%	8%	-

The waste heat potentials were calculated by following equations:

$$E_{total} = P_{total} * FLH \quad ; \quad E_i = E_{total} * TS_i \quad ; \quad WH_i = E_i * WHS_i,$$

with *P* being the installed capacity, *E* the electricity demand, *WHS* the waste heat share, *WH* the waste heat potential and *i* denoting the different technologies (AEL, PEM-EL, SOEL).

The resulting aggregated waste heat potentials are depicted in Figure 2. The global waste heat potential from electrolysers is around 440 TWh and 2,200 TWh for 2030 and 2040, respectively. Considering only the EU27 + UK, the waste heat potentials are estimated to 35 TWh and 250 TWh for the years 2030 and 2040, respectively.

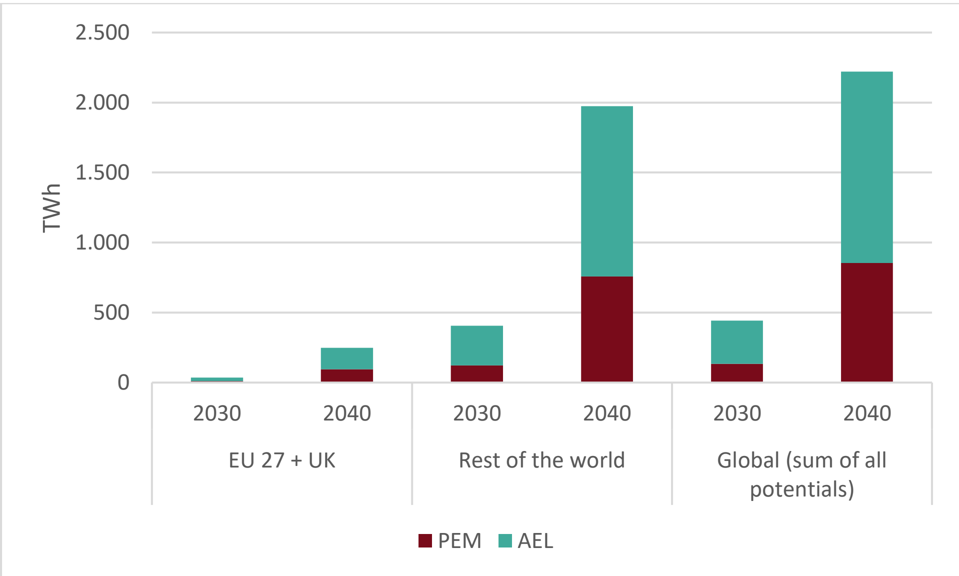

Figure 2: Waste heat potentials from electrolysers. Own calculation based on input data from [25], [29].

For the European countries, an assessment on a national level is conducted. Especially high waste heat potentials of over 20 TWh are available in Germany, France, Denmark, the Netherlands and Finland by the year 2040. For Denmark, the current final energy demand for heating purposes (including industrial heat demand) is around 80 TWh and is expected to stay in that range in the future [30]. With an expected waste heat potential of 29 TWh by 2040, theoretically about 36% of the heat demand can be covered by waste heat from electrolysers. For the Netherlands, the final energy demand for heating purposes (including industrial heat demand) was around 278 TWh in 2019 [31]. Assuming an unchanged demand in 2040, around 8% of the heat demand can be theoretically covered by waste heat from electrolysers.

3.3 Comparison to heat demand

In order to understand the magnitude of the waste heat potential, a comparison of the estimated waste heat potential for 2040 and the projected heat demand from district heating (DH) networks in 2040 has been done based on data from [32], see Table 3, right columns and Figure 3.

Table 3: National waste heat potentials (WHP) from electrolysers in GWh. Own calculation based on input data from [29]; and projected final heat demand supplied by district heating (DH) networks in 2040 in GWh based on data from [30].

	PEM WHP		AEL WHP		Total WHP			DH demand	Share
	2030	**2040**	**2030**	**2040**	**2030**	**2040**		**2040**	**2040**
AT	231	764	534	1,223	766	1,987		16,485	12%
BE	401	2,177	926	3,484	1,327	5,661		7,000	81%
BG	147	487	339	779	486	1,265		2,605	49%
CY	-	27	-	43	-	69		13	550%
CZ	243	1,228	563	1,965	806	3,193		17,020	19%
DE	2,677	14,529	6,186	23,246	8,863	37,775		66,410	57%
DK	171	11,116	395	17,786	566	28,903		24,762	117%
EE	55	258	128	413	184	671		3,436	20%
ES	505	6,837	1,168	10,939	1,673	17,775		134	13,240%
FI	401	8,432	927	13,491	1,327	21,922		30,193	73%
FR	1,081	12,552	2,497	20,083	3,578	32,635		26,637	123%
GR	194	749	448	1,198	642	1,947		612	318%
HR	83	239	191	383	274	623		3,088	20%
HU	264	941	609	1,505	873	2,446		9,842	25%
IE	111	3,788	257	6,061	369	9,849		1,500	657%
IT	1,177	6,046	2,720	9,673	3,896	15,719		8,428	187%
LT	144	473	332	757	476	1,231		3,859	32%
LU	-	34	-	54	-	88		1,151	8%
LV	54	245	124	392	178	637		3,987	16%
MT	-	-	-	-	-	-		-	-
NL	789	8,846	1,823	14,153	2,612	22,999		11,995	192%
PL	494	2,951	1,141	4,722	1,635	7,673		22,670	34%
PT	126	2,147	291	3,436	417	5,583		33	17,045%
RO	224	2,601	519	4,161	743	6,762		3,409	198%
SE	472	3,021	1,091	4,833	1,563	7,853		38,220	21%
SI	67	257	155	412	221	669		2,412	28%
SK	118	374	274	598	392	972		7,465	13%
UK	743	4,033	1,717	6,452	2,460	10,485		70,797	15%
SUM	**10,971**	**95,151**	**25,356**	**152,242**	**36,327**	**247,392**		**384,161**	**64%**

Overall, the waste heat could cover up to 64% of the final heat demand supplied by DH. In countries with a warmer climate (Cyprus, Greece, Italy, Portugal, Romania, Spain), the waste heat potential could cover 100% and far beyond of the projected heating demand in 2040. This also applies for Denmark featuring a high heat demand and a high share of DH combined with significant waste heat potentials. Additionally, countries with medium heat demand and lower shares of DH (France and Netherlands) could also cover their full DH demand. Other countries with high heat demand and low share of district heating reach about 10-80% of coverage.

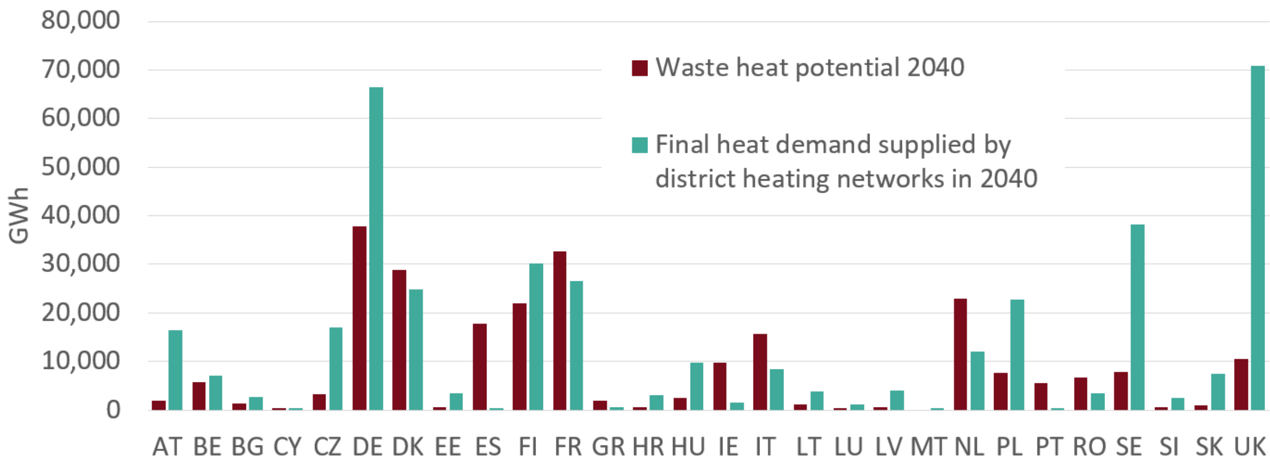

Figure 3: Comparing the estimated waste heat potential for 2040 and the projected final heat demand supplied by district heating networks in 2040 (Residential and non-residential buildings, space heating and hot water without industry [32], heat losses in the network not considered).

However, not all available waste heat potential can be used in DH networks, due to [5]:

- the seasonality of the heat demand and the possible mismatch to the waste heat availability of the hydrogen production
- the locational mismatch of the electrolysers with the DH network
- the temperature mismatch, many DH networks have higher supply temperature levels as the available waste heat [33]
- the long payback periods due to potentially high investment costs, together with rather low revenues from heat sales especially in summer times.

If due to the above reasons only 50% of the waste heat potential could be realized in DH networks, this would result in a total share of about 24%, thereby contributing significantly to the decarbonization of DH networks in Europe.

4 SUMMARY AND CONCLUSIONS

Within this paper, an assessment of the potential of waste heat from electrolysers on a national level in Europe and worldwide has been done based on scenarios for their expected capacities and key technology performance data. This potential is then compared with the projected final heat demand supplied by district heating networks.

As hydrogen is essential for the decarbonisation of different parts of our energy system, the number of installed electrolysers will increase significantly in the coming years to meet the growing demand for renewable hydrogen. The use of waste heat from electrolysers could be an important factor in increasing the overall efficiency of these installations, i.e. first demo projects show an overall system efficiency of 84-90% by utilizing the waste heat.

The evaluation shows, that in countries with low heat demand the waste heat could theoretically decarbonize the complete district heating sector and far beyond. In fact, for some countries the available waste heat potential is exceeding the final heat demand supplied by district heating networks by far, resulting in substantial efficiency losses if the waste heat is not utilized otherwise. On the other hand, in countries with high and medium heat demand, the waste heat can be an important contributor for decarbonizing district heating networks.

For boosting the system efficiency, following conclusions can be drawn:

1. The placement of electrolysers should be incentivized in countries with high heat demand and / or nearby DH networks or other larger heat consumers
2. The adaptation of existing DH networks for higher shares of waste heat from electrolysers should be supported, i.e. by reducing the district heating network temperatures [34] and increasing the seasonal storage capacity [35]
3. New DH network should be set-up nearby the location of electrolysers; preferably, this systems should be of 4th generation [36] or 5th generation [37].

5 AKNOWLEDGEMENT

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6 REFERENCES

[1] International Energy Agency, *Global Hydrogen Review 2021*. OECD, 2021. doi: 10.1787/39351842-en.

[2] IRENA, 'Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal', International Renewable Energy Agency, Abu Dhabi, 2020.

[3] Hydrogen Council, 'Hydrogen Insights. A perspective on hydrogen investment, market development and cost competitiveness', 2021.

[4] European Commission, 'A hydrogen strategy for a climate-neutral Europe: COM(2020) 301 final', 2020.

[5] Ralf-Roman Schmidt, Roman Geyer, and Pauline Lucas, 'DISCUSSION PAPER The barriers to waste heat recovery and how to overcome them?' Jun. 2020. [Online]. Available: https://ec.europa.eu/futurium/en/system/files/ged/20200625_discussion_paper_v2_final.pdf

[6] M. Ozturk and I. Dincer, 'A comprehensive review on power-to-gas with hydrogen options for cleaner applications', *International Journal of Hydrogen Energy*, vol. 46, no. 62, pp. 31511–31522, Sep. 2021, doi: 10.1016/j.ijhydene.2021.07.066.

[7] H. Böhm, S. Moser, S. Puschnigg, and A. Zauner, 'Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials', *International Journal of Hydrogen Energy*, vol. 46, no. 63, pp. 31938–31951, Sep. 2021, doi: 10.1016/j.ijhydene.2021.06.233.

[8] Danish Energy Agency and Energinet, 'Technology Data – Renewable fuels', 2022. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

[1] https://www.iea-dhc.org/the-research/annexes/annex-xiii/annex-xiii-project-02

[9] J. Li, J. Lin, Y. Song, X. Xing, and C. Fu, ‘Operation Optimization of Power to Hydrogen and Heat (P2HH) in ADN Coordinated With the District Heating Network’, *IEEE Transactions on Sustainable Energy*, vol. 10, no. 4, pp. 1672–1683, Oct. 2019, doi: 10.1109/TSTE.2018.2868827.

[10] S. Shiva Kumar and V. Himabindu, ‘Hydrogen production by PEM water electrolysis – A review’, *Materials Science for Energy Technologies*, vol. 2, no. 3, pp. 442–454, Dec. 2019, doi: 10.1016/j.mset.2019.03.002.

[11] A. Buttler and H. Spliethoff, ‘Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review’, *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2440–2454, Feb. 2018, doi: 10.1016/j.rser.2017.09.003.

[12] Sunfire GmbH and Salzgitter AG, ‘Press release: World’s Largest High-Temperature Electrolyzer Achieves Record Efficiency’, 2022.

[13] ‘MPREIS Wasserstoff’. https://www.mpreis.at/wasserstoff (accessed Apr. 07, 2022).

[14] C. Stabenau and W. GmbH, ‘Pilotprojekt „Power to Gas“ Ibbenbüren’, p. 19.

[15] ‘RWE-Demonstrationsanlage Ibbenbüren’. https://www.powertogas.info/projektkarte/rwe-demonstrationsanlage-ibbenbueren/ (accessed Apr. 07, 2022).

[16] ‘WindGas Falkenhagen’. https://www.powertogas.info/projektkarte/windgas-falkenhagen/ (accessed Apr. 07, 2022).

[17] ‘20180420_pm_eroeffnung_falkenhagen_de_v1.7_logo.pdf’.

[18] Green Hydrogen Esslingen GmbH, ‘Green Hydrogen Esslingen’, 2022. https://green-hydrogen-esslingen.de/ (accessed Apr. 26, 2022).

[19] Els van der Roest, Theo Fens, Ron Bol, Hans Huiting, and Ad van Wijk, ‘Heat utilization from hydrogen production: An example of local energy system integration’, presented at the 8th International Conference on Smart Energy Systems, Aalborg, 2022.

[20] ‘Hydrogen plants to provide new source of renewable heat for South Holland’, Feb. 12, 2021. https://www.portofrotterdam.com/en/news-and-press-releases/hydrogen-plants-provide-new-source-renewable-heat-south-holland

[21] Miljanovic, Andrea and Jonsson, Fredrik, ‘Utilization of waste heat from hydrogen production: A case study on the Botnia Link H2 Project in Luleå, Sweden’, Mälardalen University, School of Business, Society and Engineering, 2022. [Online]. Available: https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1670187&dswid=4859

[22] F. Mezzera, F. Fattori, A. Dénarié, and M. Motta, ‘Waste-heat utilization potential in a hydrogen-based energy system - An exploratory focus on Italy’, *International Journal of Sustainable Energy Planning and Management*, vol. 31, pp. 95–108, May 2021, doi: 10.5278/ijsepm.6292.

[23] S. Paardekooper *et al.*, ‘Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps’, Aalborg Universitetsforlag, Report, Oct. 2018.

[24] ENTSO-E and ENTSOG, ‘TYNDP 2022: Scenario Report’, 2022.

[25] IEA, ‘The Future of Hydrogen: Seizing today’s opportunities’, 2019.

[26] Danish Ministry of Climate, Energy and Utilities, ‘The Government’s strategy for Power-to-X’, 2021.

[27] H. Böhm, A. Zauner, D. C. Rosenfeld, and R. Tichler, ‘Projecting cost development for future large-scale power-to-gas implementations by scaling effects’, *Applied Energy*, vol. 264, Apr. 2020, doi: 10.1016/j.apenergy.2020.114780.

[28] ENTSO-E and ENTSOG, 'TYNDP 2022: Scenario Building Guidelines', 2022.

[29] ENTSO-E and ENTSOG, 'TYNDP 2022 Scenario Report – additional Downloads', 2022. https://2022.entsos-tyndp-scenarios.eu/download/ (accessed Apr. 25, 2022).

[30] Danish Energy Agency, 'Comprehensive Assessment 2020 - Denmark', 2020.

[31] Netherlands Enterprise Agency, 'Heating and Cooling Potential Analysis: An assessment of the potential for an efficient heating and cooling supply in the Netherlands', 2020.

[32] Lukas Kranzl *et al.*, 'Hotmaps Project, D5.2 Heating & Cooling outlook until 2050, EU-28, 2018 www.hotmaps-project.eu'. [Online]. Available: https://gitlab.com/hotmaps/scen_ambitious_building_demand

[33] R. Geyer, J. Krail, B. Leitner, R.-R. Schmidt, and P. Leoni, 'Energy-economic assessment of reduced district heating system temperatures', *Smart Energy*, vol. 2, p. 100011, 2021.

[34] P. Leoni, R. Geyer, and R.-R. Schmidt, 'Developing innovative business models for reducing return temperatures in district heating systems: Approach and first results', *Energy*, vol. 195, p. 116963, 2020.

[35] M. Köfinger *et al.*, 'Simulation based evaluation of large scale waste heat utilization in urban district heating networks: Optimized integration and operation of a seasonal storage', *Energy*, vol. 159, pp. 1161–1174, 2018.

[36] H. Lund *et al.*, '4th Generation District Heating (4GDH)', *Energy*, vol. 68, pp. 1–11, Apr. 2014, doi: 10.1016/j.energy.2014.02.089.

[37] S. Buffa, M. Cozzini, M. D'Antoni, M. Baratieri, and R. Fedrizzi, '5th generation district heating and cooling systems: A review of existing cases in Europe', *Renewable and Sustainable Energy Reviews*, vol. 104, pp. 504–522, Apr. 2019, doi: 10.1016/j.rser.2018.12.059.

RENEWABLES VS. WASTE HEAT? LEGAL PROVISIONS ON THE ORIGINAL ENERGY SOURCE

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Abstract: The Renewable Energy Directive (EU) 2018/2001 (RED II) lists ”renewable heat“ and ”waste heat“ together for heat supply within Article 24 (4) and partly also in Article 23. This paper analyses, by using basic legal and economic theory methods, (i) why a distinction is made between ”renewable heat“ and ”waste heat“, (ii) why they are mentioned in parallel, and (iii) what short-term and long-term effects this distinction implies on the use of waste heat in energy cooperation. The first conclusion of the paper is that the distinction is appropriate. However, second, the use of waste heat from fossil processes is thus not only subject to the risk of process modification (switch to renewables), but also to the political risk of non-eligibility for meeting the targets of RED II or subsequent directives. In order to minimize investment uncertainty for energy cooperation projects, especially between industry and district heating operators, we conclude that all types of waste heat should be recognised as carbon-neutral, and CO2 emissions should be attributed exclusively to the “first-use”, i.e., the industrial processes, and their conversion should be the goal of policy measures.

Keywords: waste heat and cold, RED II, EED, renewable energy system, energy cooperation

1 INTRODUCTION

The Renewable Energy Directive (EU) 2018/2001 (RED II) enforces the use of renewable energy sources (RES) and waste heat & cold in the heating and cooling sector [1]. The RED II therefore directly addresses the heating sector in Articles 23 and 24. In order to achieve the long-term decarbonisation goals, the share of renewables in the sector is to be gradually increased according to Article 23. Member States shall endeavour to increase the share of RES in the heating sector by an average of 1.1 percentage points/year in the reporting periods 2021 - 2025 and 2026 - 2030, starting from the 2020 level. This factor increases to an average of 1.3 percentage points/year in the above-mentioned periods if Member States decide to take waste heat into account. Waste heat can only be counted up to 40% of the annual increase. Up to now the targets are indicative, which means not binding for the Member States. The use of waste heat to meet the heating and cooling target is optional for Member States that do not have significant district heating systems, as waste heat and cold are only eligible if they are used in district heating systems. Even Member States where such infrastructure has been developed may choose not to use waste heat to reach the district heating targets. The reason could be that they want to focus more on renewable heating and cooling. The European Legislator recognised that, given the local and national character of the heat markets, it is of utmost importance to ensure flexibility in the design of such a scheme. Therefore, Member States are free to use appropriate measures and the RED II provides several instruments on how to achieve the increase. These include policy measures, e.g., fiscal measures or other financial incentives, on which an introduction of a national CO2 tax on the heat market (non-ETS sector) and appropriate support schemes to increase the share of renewable heat could be based on [2].

Article 24 RED II is dedicated to district heating. It focuses on the great potential for decarbonisation through higher energy efficiency and the use of renewable energies. With regard to the further decarbonisation of district heating systems, under Article 24 (4) the Member States were given two options to choose from, which can also be combined:

- The share of renewable energies and waste heat and cold in district heating and cooling systems should be increased by at least 1 percentage point/year. To reach the district heating target, the use of waste heat or cold is not subject to a cap, which means the total average annual increase of one percentage point can also be fully achieved with waste heat or cold (Option 1) or
- the district heating networks are to be opened up to suppliers of energy from renewable energy sources and of waste heat and cold (to connect and purchase heat from renewable energy sources and waste heat and cold from third-party suppliers on the basis of non-discriminatory criteria) (Option 2).

A sustainable energy system uses only renewable primary energy sources and applies them in a resource-efficient manner [3]. There, energy efficiency is an option for satisfying demand and avoiding unnecessary use of resources, as also renewable resources are limited. The recovery of unavoidable waste heat is a straightforward measure to increase overall energy efficiency. Waste heat already comes from a process, so the energy is used a second time, and the reuse reduces the primary energy demand. Thus, we conclude that the RED II also aims at a sustainable energy system. The directive mentions RES and waste heat as options for meeting the heat demand. In Article 24 (4) of RED II, there is a consistent juxtaposition of renewable energy sources and waste heat and cold. However, there is no common definition which summarizes/includes RES and waste heat, like, just for example, “climate-neutral heat” would be. These two options, RES and waste heat, are neither congruent nor exclusive within Article 24 (4). Legally, there is no differentiation within the definition of waste heat in terms of the respective original energy input, i.e., whether it is obtained from a fossil or renewable process.

2 AIM OF THE PAPER AND METHOD

A sustainable energy system is defined to use 100% renewable primary energy sources and use them in a resource-efficient manner [3]. We assume that the RED II aims to achieve a sustainable energy system. The aim of the paper is to analyse, first, whether the distinction of RES and waste heat is appropriate, and whether the consistent juxtaposition is appropriate. This task is done by legal analysis and interpretation of the definitions that are captured in the RED II. The second aim of the paper is to classify these findings and the RED II’s handling of waste heat and its likely practical on the realization of waste heat recovery and reuse projects, including the implicit consequences for the use of waste heat from fossil processes. This is done from a basic economic theory perspective, taking into account statements from previous work [4], [5], [6].

3 LEGAL ANALYSIS OF DEFINITIONS

As shown above, the RED II mentions RES and waste heat as options for covering the heat requirement. Therefore, a precise, understandable definition of the term is absolutely necessary to ensure that the allocation to the corresponding energy flows in a specific project is correct: based on the legal definition, is the heat to be categorized as waste heat, RES or can the heat not be allocated due to the complex definitions? For this reason, it is important at the beginning of this analysis to understand what the European Legislator understands by the terms “renewable energies” and “waste heat”. Relevant definitions from the RED II are presented in Table 1 below.

Table 1: Overview of respective definitions under RED II

Article 2 (1) ‘energy from renewable sources’ or ‘renewable energy’	means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas
Article 2 (9) ‘waste heat and cold‘	means unavoidable heat or cold generated as by-product in industrial or power generation installations, or in the tertiary sector, which would be dissipated unused in air or water without access to a district heating or cooling system, where a cogeneration process has been used or will be used or where cogeneration is not feasible
Article 2 (2) ‘ambient energy’	means naturally occurring thermal energy and energy accumulated in the environment with constrained boundaries, which can be stored in the ambient air, excluding in exhaust air, or in surface or sewage water

Article 2 (1) makes clear what is meant by RES and even lists them exhaustively. This clarity does not apply to the definition of waste heat, which is quite complex and not fully comprehensible, at least at a first glance. Therefore, it will now be broken down into its various components and an attempt will be made to explain the individual parameters of this definition in a comprehensible way. "Waste heat and cold" means, first,

1. unavoidable heat or cold that is
2. generated as a by-product in an industrial plant, in an electricity generation plant or in the tertiary sector, and that
3. that would be discharged unused into air or water.

   If these conditions hold,

4. there must not be access to a district heating system or a district cooling system,
    - where a cogeneration process is used,
    - where a cogeneration process will be used or
    - where a cogeneration process is not possible.

The first three parameters refer to the conditions of the heat within the limits of the operation (unavoidable, by-product, unused). They reflect the general technical understanding of waste heat (whereby we do not dive into the discussion on the wording and alternative wording, e.g., excess heat, residual heat, etc.). The last parameter now represents additional conditions for the possibility of use in the environment. This definition of waste heat, as it is ultimately stated, serves the intentions of Articles 23 and 24 RED II; however, as it refers to a district heating system or a district cooling system, it cannot be a universally applicable definition of waste heat.

3.1 Unavoidability of waste heat

First, waste heat is “unavoidable” heat. According to Article 14 (5) of Energy Efficiency Directive (EU) 2018/2002 (EED), it can be concluded that “unavoidable” means that all other feasible energy efficiency options to reduce waste heat have been exhausted. The technical and economic feasibility of applying these energy efficiency options must be analysed.

An unavoidable waste heat stream is one that cannot be recovered within the same process or plant. The technical and economic feasibility of applying energy efficiency options must be analysed and all “reasonable” efficiency measures must be implemented first.

Therefore, the relevant provisions of the EED and RED II require that all reasonable energy efficiency measures should be applied first. Before off-site use can be considered, the technical and economic feasibility of applying energy efficiency options and on-site use must be analysed, and any reasonable efficiency measures must be implemented first. In the longer term, therefore, advances in best available technology (which affect the definition of what is reasonably unavoidable) will affect the availability of waste heat for sale [7]. Only then should waste heat be used to achieve the targets of the RED II, so only after all options for reducing energy demand have been exhausted. This sequence for dealing with waste heat is an application of the Energy Efficiency First principle.

3.2 Waste heat as a by-product

The next essential criterion for waste heat is its occurrence as a by-product within a process. According to Recital 117 RED II, it can be concluded that by-products are defined by the fact that they are not the primary objective of the production process. Accordingly, “by-product” within Article 2 No. 9 RED II would mean that waste heat was not intentionally generated – the generation of energy in the form of waste heat is not the objective of the process. The generation of waste heat must not be the main purpose of the process [8]. Here the question arises, to what extent heat is a by-product in a CHP (combined heat and power) plant. A plant designed for co-generation shall not produce heat as a by-product. However, based on current power market prices and local heat availability, a distinction according to the operating modes “electricity-led” or “heat-led” of the CHP plant could be decisive for the (non-)fulfilment of some definition criteria. Consequently, although this is technically hardly arguable, there might be an economic reason for distinction.

According to RED II Annex 5 lit C Z 16, heat from a CHP is referred to as “useful heat”. The directive means that heat is “produced in a CHP process to meet an economically justifiable demand for heating or cooling”. However, the Directive does not assign the term “useful heat” to either renewable energy sources or waste heat - thus it is not clear whether this “useful heat” can be counted towards the requirements of Article 24 (4) in the district heating sector.

3.3 Waste heat from industry, electricity generation and the tertiary sector

Waste heat also be recovered from plants that are clearly assignable as industrial plants, electricity generation plants or tertiary sector plants. Other installations that take over municipal tasks, such as waste incineration plants, are much discussed, but there are no clear statements in the RED II as to whether they fall under one of the three categories of plants.
In Austria, however, this can be concluded from some materials, for example in the adopted amendment to the government bill 733, where it is written in chapter 8 that “the term "waste heat" is replaced by the definition according to § 5 (1) no. 1 Renewable Energy Expansion Act. This also includes, for example, waste heat from waste incineration plants as well as waste heat that is used within the framework of a combined heat and power system. " And also, in the explanations to the adopted amendment to the Umweltförderungsgesetz it is written that "waste heat can be included if it arises in industrial processes (including waste incineration), in the tertiary sector or in CHP plants."

3.4 Dependency on the availability of district heating and CHP

There are additional provisions on the district heating network and cogeneration which must be fulfilled so that the heat actually is waste heat: The definition’s second part is difficult to read (we almost dare to say incomprehensible): “without access to a district heating or cooling system, where a cogeneration process has been used or will be used or where cogeneration is not feasible”. In order to understand the included scenarios, it needs to be split up:
Heat fulfilling the conditions of being (1) unavoidable, (2) unintended (i.e., by-product) and (3) otherwise disposed, is waste heat by RED II definition, if

a. there is no access to a DHC system with CHP
b. there is no access to a DHC system with the future use of CHP
c. there is no access to a DHC system in which CHP is not possible.
   Heat fulfilling the conditions 1 through 3 is not waste heat by RED II definition, if
d. there is no access to a DHC system in which no CHP is used (even in the future, although it would be possible)
e. there is access to a DHC system with CHP
f. there is access to a DHC system with the future use of CHP
g. there is access to a DHC system in which CHP is not possible
h. there is access to a DHC system in which CHP is not used (even in the future, although it would be possible).

The consequences are discussed below.

4 DISCUSSION

Is it appropriate to distinguish between the two heat sources RES and waste heat, and if yes, how should they be weighed by legislation? The answer to the first question is simple: While fossil and renewable energy are to be viewed separately, unavoidable/unintended/elsewise disposed waste heat can occur from both, processes with original fossil and RES input. Thus, waste heat and RES are not the same and distinguishing between them is appropriate. Accordingly, the RED II and our legal analysis of its definitions comes to the conclusion that there is no differentiation within the definition of waste heat in relation to the respective input energy use, i.e., if it is recovered from a fossil or renewable process. Based on the argument, a 2x2 matrix can be derived, which represents the possible sources of the heat supply. In this simplified figure, we neglect potential transitions between and single cells (e.g., ambient energy, as described above) as well as known discussions on e.g., life cycle emissions. From this figure and based on literature statements, we want to clarify how legislation should handle RES vs. waste heat.

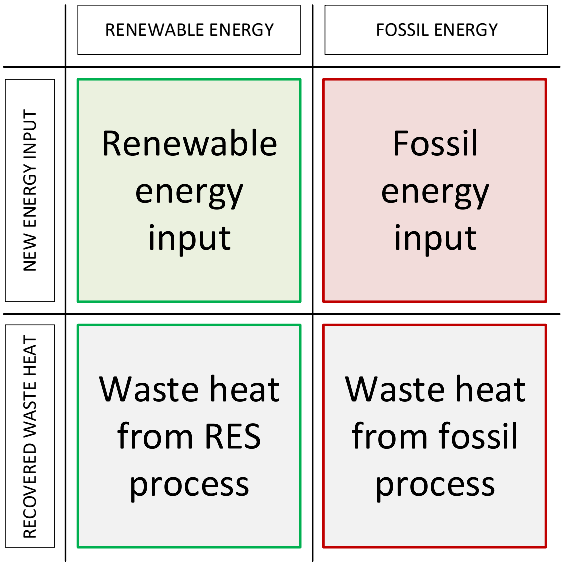

Figure 1: Four possible sources of district heating heat supply (Source: Energieinstitut an der JKU Linz)

The upper right box is the one to be avoided as it complies with none of the two requirements of a sustainable energy system. The lower left box is the optimum as, obviously, using waste heat from processes with RES input is the long-term goal. Ideally, it is possible to transform the heat supply of a district heating system from the upper right box to the lower left box.

- Waste heat from fossil processes (lower right box) is often regarded as being fossil itself. From an economic point of view, significant turnover from selling waste heat may result in reluctance to modify or fuel-switch fossil processes, causing a so-called lock-in effect. However, most of the time waste heat revenues are negligible compared to process costs. As fossil processes will be existent in the short to medium term, using their waste heat to avoid direct heat energy input remains an option. Moreover, in a sustainable energy system, fossil processes shall not exist (due to carbon pricing or prohibition), and thus, in the long run, waste heat from fossil processes is not available.
- In a sustainable energy system, efficient use is crucial. RES do not have unlimited potential. Low-temperature energy demand should be supplied by low-temperature sources like waste heat, as a cascaded and exergy-oriented use increases primary energy efficiency. High-quality RES should supply high-quality needs. Despite of that, using RES for heating is a definite step towards carbon neutrality and can be chosen if RES are available at low costs and do not undermine high-quality usage.

Based on this qualitative illustration, it is not clear whether direct renewable energy input or waste heat from existing fossil processes should be given preference. Therefore, we consider the approach of the RED II to mention RES and waste heat them in parallel to be appropriate.

4.1 The preference of RED II for RES

The eligibility of waste heat and cold does not depend on the original fuel used at the source process. Any waste heat can be used to meet the heating and cooling sector target, and the DHC subsector target, whether it comes from biomass, renewable electricity, or fossil fuels.

Heat or cold used externally that could not be used internally is considered equivalent to RES under Article 24 (4) of the RED II.

- But it does not count towards the overall EU renewables target or national renewable energy contributions.
- Furthermore, there are percentage requirements in the RED II, defining a minimum share of the targets to be achieved with RES (and not with waste heat).

This can clearly be interpreted as a preference of the RED II towards RES which implies that Member States can exceed the requirements of the RED II in their national implementation and that there is a certain probability that amendments of the RED II put even higher preference to RES. While waste heat from RES is probably not affected (it is also positioned in the left “renewable column” in the box above), there are significant uncertainties for the use of waste heat from fossil processes. The use of waste heat from fossil processes is not only subject to the “usual” risk of (i) process modification (e.g., when switching to RES) but now also to (ii) non-eligibility for meeting the national targets of RED II or subsequent directives [13], [14]. This will result for a waste heat user who is able to decide whether to use one MWh from waste heat or RES, to decide in favor of RES, “ceteris paribus”. If the risk of non-eligibility remains, the aversion to waste heat from fossil processes increases and it will remain unused. We identify essential problems arising from impending non-eligibility: There are industrial sites that are not connected to district heating or do not provide waste heat to other local companies that can use the waste heat. In some cases, industrial process modification will be simple (e.g., switch steam boilers to green gas fired ones) and will not affect waste heat amounts, in other cases process modification will be complicated (e.g., hydrogen steel making) but companies will remain on-site and will still show waste heat flows (maybe other volumes, temperatures, profiles). However, as these companies are not connected today – due to the risks derived from RED II – companies or district heating systems that could be supplied from waste heat will then rely on RES plants, i.e., district heating companies will have invested in RES solutions to comply with the directive. Then, the integration of waste heat (then: “RES waste heat”) will not happen due to economic reasons – the same ones as today (economic feasibility, trust, backup issues, etc.).

4.2 Incomprehensible definition

The above subsection explains an uncertainty resulting from a political process, demanding more clarity for the transformation process in general. However, further uncertainty comes from the definition on waste heat [12]. Normally, definitions should help to clarify what is meant, but the RED II definition on waste heat even increases unclarity. It is only one fact that the definition of waste heat is so narrowly but at the same time unclearly regulated. This narrow interpretation can lead to uncertainties in the case of planned waste heat utilisation. If one of the parameters listed above is not clearly identifiable, the heat used may not be counted as waste heat according to Article 2 no. 9 and subsequently not be counted towards the targets according to Article 23 or 24 of RED II.

- First, and already elaborated above, the definition leaves open if heat from CHP is accountable as waste heat, due to not being a by-product from *co*generation from a technical perspective.
- Second, the definition’s second part increases unclarity. It is not clear (i) what these additional provisions aim for, (ii) what their added value to the points 1-3 is and (iii) and whom they support or restrict. Moreover, the additions do not appear arguable. Neither

experts nor the RED II's recitals can help here. Some experts identify a support for CHP, but points a-c suggest that a plant's residual heat is waste heat, if DHC system does *use* a CHP (points a, b, c), which is to be substituted. While CHP sustain a high level of exergy through electricity generation, they are a few percentage points behind a heat-only boiler in terms of overall efficiency. Industrial residual heat would not be accounted as waste heat if the plant is already connected to the district heating network. Perhaps what is also meant is that if a CHP is present during operation, its residual heat does not count as waste heat; but this cannot be read from the definition.

4.3 Excursus: contradictions with "ambient energy"

According to Article 2 No.1, ambient energy counts as RES. Remarkably, the heat recovered from the wastewater system is considered ambient heat and thus renewable, but not waste heat. As for waste heat, there is also no distinction made if the wastewater is warmed by RES or fossil fuels, nevertheless this ambient heat always is RES. Wastewater heat can be recovered either from the sewage system, like a building sewer, wastewater pipes or a wastewater treatment plant. Naturally, wastewater is mainly found near cities and conurbations and thus potentially usable in district heating. Based on the definition of waste heat in the RED II, one could argue that at least the share of wastewater heat that is a by-product of industry or the service sector should be considered waste heat. However, there seems to be no easy way to calculate the shares of wastewater from the household sector and other sectors once they have been combined in wastewater pipes [9].
Industrial and power plant cooling systems either dispose energy to air or water. Therefore, the question arises why exhaust air is excluded when wastewater is included in the definition of ambient energy. The energetic difference is not clear between exhaust air heated by industrial processes and wastewater heated by the discharge of industrial waste heat [10]. RED II recognises heat pumps as renewable energy technologies according to Recital 49 RED II, and it is recognised that outdoor air is a renewable energy. In this context, it is not clearly argued why other technologies that use exhaust air are not treated in the same way as renewable energies in the directive. After all, exhaust air contains energy that is readily available but is lost outside the building/industrial furnace if it is not recovered. Using exhaust air as a heat source is more efficient than using outside air because of its higher temperature and it seems questionable why to treat recovered exhaust air differently from ambient air [11]. Accordingly, the directive with its definition of ambient energy is not always coherent and conclusive and makes no difference concerning the primary energy input.

5 CONCLUSIONS

In Article 24 (4) of RED II, heat from RES and waste heat are largely treated similarly. This approach of legally distinguishing renewable energy sources and waste heat, but treating them largely the same, is appropriate. However, the definition of waste heat has urgent need to become clear, so that there may not be a misunderstanding whether the used heat is waste heat at all and can be counted towards the targets of the RED II. When transposing the directive into national law, the national legislator could create a clear and detailed understanding of waste heat and its interrelation with RES and, for example, ambient heat. Another alternative for clarification is to leave out the incomprehensible second part of the waste heat definition.

Waste heat is considered equivalent to renewable energy under Articles 23 and 24 of the RED II but it does not count towards the overall EU renewables target or national renewable energy contributions. Moreover, the contribution of waste heat is limited in the overall heat and cold target. If society strives for a sustainable energy system, the aim is the exergy-efficient provision of DHC with waste heat that comes from a process originally supplied with RES. (i) When DHC systems only switch from fossil to renewable energy input, processes' waste heat is likely to remain unused, and it is likely that also the waste heat from processes with RES as original energy input remains unused. (ii) If waste heat from a process with fossil energy input is connected to a DHC system, it is likely that waste heat will also be used after a decarbonizing process modification. Thus, waste heat from fossil input energy should be politically accepted in order to increase investment certainty for use in DHC systems, and, equally important, at the same time, the switch of industrial processes and power plants to RES must be politically enforced.

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7 REFERENCES

[1] This paper was elaborated within the NEFI project "HeatHighway". This text was also submitted and presented within ISEC 2021.

[2] AFGW (2020), Die Erneuerbare-Energien-Richtlinie und ihre Bedeutung für Fernwärme, www.afgw.de

[3] Böhm, Moser, Puschnigg, Zauner (2021) Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials. International Journal of Hydrogen Energy, Volume 46, Issue 63, 13 September 2021, Pages 31938-31951, https://doi.org/10.1016/j.ijhydene.2021.06.233.

[4] Holzleitner, Moser, Puschnigg (2020) Evaluation of the impact of the new Renewable Energy Directive 2018/2001 on third-party access to district heating networks to enforce the feed-in of industrial waste heat. Utilities Policy, Volume 66, October 2020, 101088, https://doi.org/10.1016/j.jup.2020.101088.

[5] Moser, Lassacher (2020) External use of industrial waste heat - An analysis of existing implementations in Austria. Journal of Cleaner Production, Volume 264, 10 August 2020, 121531, https://doi.org/10.1016/j.jclepro.2020.121531.

[6] Moser, Puschnigg, Rodin (2020) Designing the Heat Merit Order to determine the value of industrial waste heat for district heating systems. Energy, Volume 200, 1 June 2020, 117579, https://doi.org/10.1016/j.energy.2020.117579.

[7] Energy Community (2021), How would heating and cooling sector contribute to EU 2030 decarbonisation goal – NECPs measures, Discussion Paper by the Energy Community Secretariat, 2021.

[8] European Commission (2020), Waste heat in the context of REDII, EED and EPBD, www.ca-res.eu

[9] European Commission, Joint Research Centre (2021), Kavvadias et al, Defining and Accounting for Waste Heat and Cold, https://publications.jrc.ec.europa.eu/repository/handle/JRC126383
[10] Jouhara et al (2018), Waste heat recovery technologies and applications, Thermal Science and Engineering Progress, Volume 6, June 2018, Pages 268-289.
[11] EVIA (2017), Renewable Energy Directive: Why Heat Recovery should be treated in the same manner as Renewable Energy, www.evia.eu
[12] FGW (2021), Stellungnahme des Fachverbandes der Gas- und Wärmeversorgungsunternehmungen (FGW) zur Überarbeitung der Richtlinie zur Förderung der Nutzung von Energie aus erneuerbaren Quellen (Renewable Energy Directive – RED III)
[13] BMNT (2019), Integrierter nationaler Energie- und Klimaplan für Österreich, www.bmk.gv.at
[14] BMNT/BMVIT (2018), #mission2030 – die österreichische Klima- und Energiestrategie, www.bmk.gv.at

III. Presentations: Disruptive technologies for a decarbonized energy system

THE AUSTRIAN ELECTRICITY SECTOR'S DEPENDENCE ON NATURAL GAS AND A WAY OUT

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Abstract: The gas crisis has led to an unprecedented increase in electricity prices and could potentially threaten security of supply. In 2020, around 17% of Austria's electricity consumption was covered by gas generation. In order to curb this dependency and the associated price driver, it is necessary to implement the energy turnaround as quickly as possible. For this paper, the LEGO optimisation model is used to map the possible effects of gas supply shortages for the years 2022 and 2030 on the electricity sector. For the year 2022, a reduction of gas generation by 80% could lead to a supply shortfall of up to 7.6 TWh. In 2030 with the Renewable Expansion Act (EAG) goals achieved, the same reduction would only lead to non-supplied energy of up to 1.5 TWh. Allowing for additional generation expansion beyond the EAG targets, it would also be possible to replace fossil gas generation in the electricity sector entirely by renewable energy sources. This would not only save gas, which is more urgently needed in other sectors for the time being, but would also be a big step towards climate neutrality.

Keywords: renewable energies; energy system modelling; LEGO; power system; generation expansion

1 INTRODUCTION

The Ukraine conflict is having a major impact and putting further pressure on the already strained energy market. First, the current gas supply situation is the main price driver for the electricity price, as gas power plants are the marginal technology to set the price in a merit-order system. Second, it also reveals questions in the security of supply, as Austria is importing 80% of its natural gas from Russia.

The Renewable Expansion Act (EAG), which was already passed in 2020, defines that 100% of Austria’s electricity demand has to be covered by renewable energies by 2030 net-nationally. In order to achieve this, 27 TWh are to be added, of which 11 TWh are accounted for by photovoltaics (PV), 10 TWh by wind, 5 TWh by hydropower and 1 TWh by biomass [1]. PV and hydropower have their generation peak in the summer months, which means that Austria is already mostly an electricity exporter in these months. In the other half of the year, Austria is currently dependent on imports and generation from fossil gas. As outlined above, in order decrease the dependency on gas imports and ensure security of supply, while respecting binding climate targets further expansion of renewables (exceeding the EAG targets) might be required.

2 MATERIALS AND METHODS

The case studies were carried out using the Low-carbon Expansion Generation Optimisation (LEGO) open source model, developed at the Institute of Electricity Economics and Energy Innovation, which is available on GitHub[1]. The LEGO model is flexible in two directions, once in time and once in the blocks used. Its general structure and individual building blocks are depicted in Figure 2-1. LEGO is formulated as a cost-minimisation problem. This includes operational and investment costs. In the following we provide some information about the model features considered in the case studies. In all of the cases LEGO is run as a mixed-integer program (MIP) and (depending on the case) we consider either an operation-only or expansion planning problem. The model is based on a power balance principle and the power flow is represented as direct current optimal power flow (DC-OPF). For detailed information about LEGO's mathematical framework, the interested reader is referred to [2].

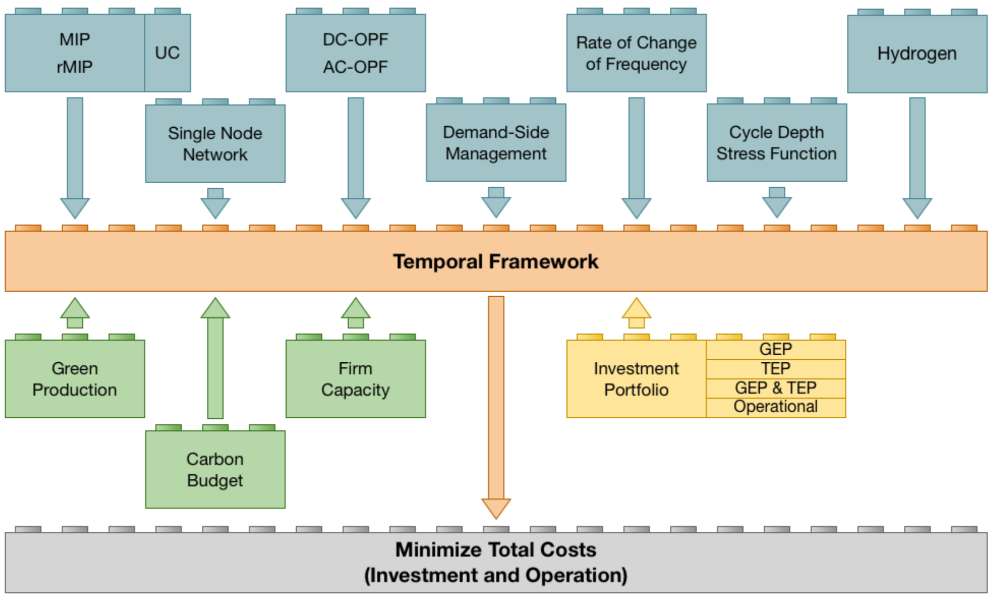

Figure 2-1: LEGO model blocks [8]

In order to keep the computational effort low, seven representative days with 24 hours were determined with the help of the clustering algorithm k-medoids, for which the actual values from the year 2020 of consumption, the difference between import and export, generation from PV and wind, generation from gas power plants, as well as the inflow data for run-of-river power plants and (pump) hydro storages of a determined standard year were used. The implementation of the Austrian transmission grid was carried out using a detailed grid map from [3] and line data from Austria's transmission system operator APG [4]. The digital twin of Austria's transmission system, as seen in Figure 2-2, consists of 251 lines, 175 transformers, 7 phase-shifting transformers and 196 nodes (power stations). For renewable generation, hourly capacity factors were downloaded for each node from Renewable Ninjas [5]. After the

[1] https://github.com/IEE-TUGraz/LEGO

implementation of all data, the model was calibrated to the generation values of the year 2020. For the year 2022, the status of the installed capacity at the end of 2021 was used; for the year 2030, the expansion of the EAG was assumed. The location of the expansion of PV was carried out as described in [6], and that of wind as in [7]. Table 2-1 shows the installed capacity in the respective years.

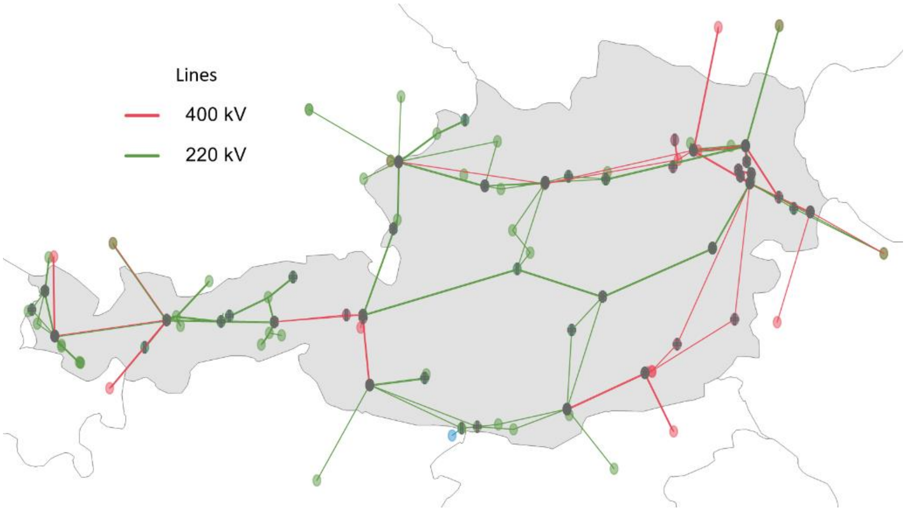

Figure 2-2: Digital Twin of the Austrian transmission network for 2022

As Austria is importing 80% of natural gas from Russia, we look at two scenarios in this paper: What impact would a sudden stop of gas supply from Russia have on Austria's power sector, assuming that only 20% of gas generation of 2020 would be possible? The second scenario investigates Austria's electricity system in 2030, comparing the results of just achieving the EAG goals, how that would look like completely without gas, and what investments would be necessary to become independent of gas?

Table 2-1: Installed Capacity of the Austrian power system

	2022	**2030**
	[MW]	**[MW]**
Wind	3 301	7 150
Photovoltaics	4 343	13 043
Biomass	613	727
Natural Gas	3 705	3 060
Oil	187	187
Run of River	5 571	6 195
(Pump-) Storages	8 799	10 972
Others	92	46

3 RESULTS

3.1 Reduction of gas generation in the electricity sector by 80% compared to 2020 in 2022

The first scenario is intended to show the possible effects of an import stop of Russian gas on generation in 2022. For this purpose, gas production was reduced to 20% of the production in 2020. Imports and exports in this scenario were assumed to be the same as for 2020.

Figure 3-1 presents the impact of a reduction of gas generation by 80% in Austria's electricity system for 2022. The first scenario shows generation without any constraints on generation from gas. In this case, 11.6 TWh were generated from gas. The second scenario shows the same case only with gas generation restricted to 2.35 TWh (80% cut), which means that the more expensive oil-fired power plants are also used, but still 7.6 TWh of non-supplied energy remain. We conclued that an 80% gas cut in the power sector could potentially lead to a loss of load of about 11% of Austria's total annual power demand.

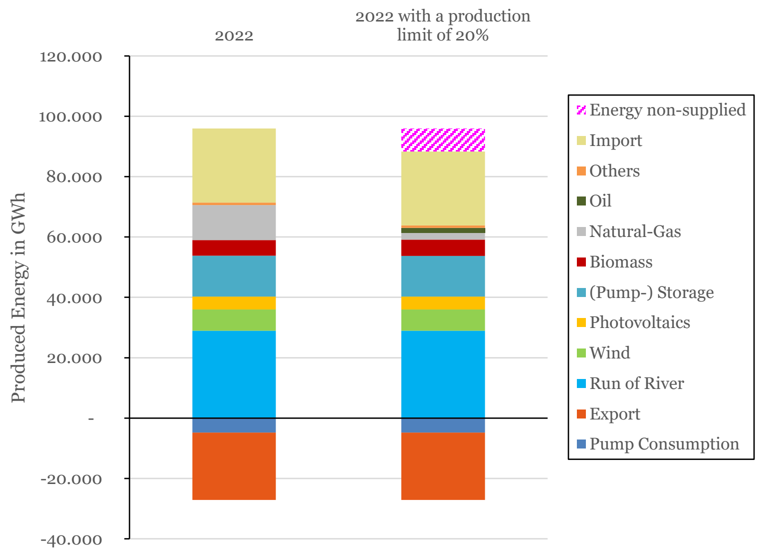

Figure 3-1:Comparison between the normal case of 2022 and the case with a gas production limit of 20%

Figure 3-2 shows the monthly generation of the 2022 scenario with an 80% gas production cut. In the months of October to March, the share of undelivered energy is between 15.9% and 19%, and even in April it is still 11.3%. This means that most energy is missing in the winter months, when consumption is highest and generation is lowest. One solution to eliminate non-supplied energy would be to reduce exports and raise imports.

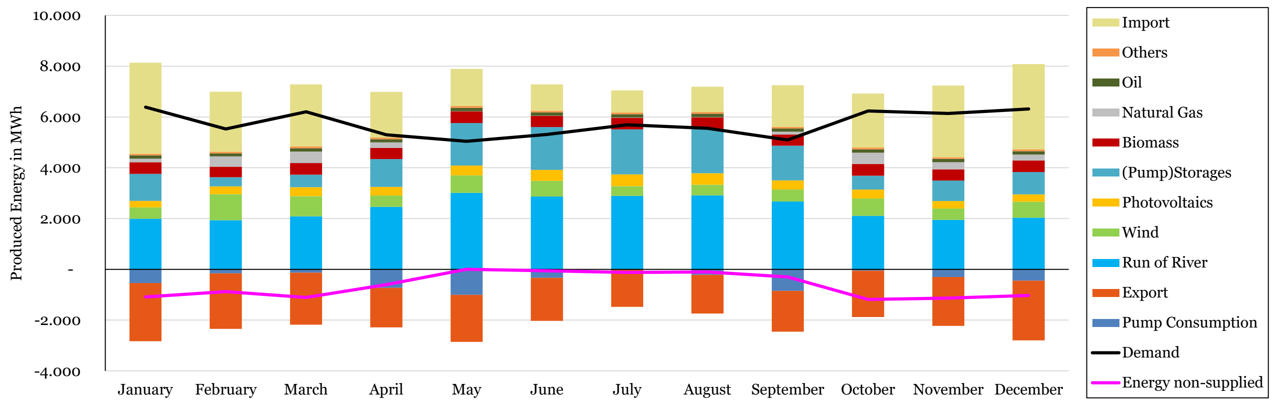

Figure 3-2:Generation, consumption and non-supplied energy by month for the 80% gas supply cut scenario

3.2 Gas generation in 2030 and the path out of it

For 2030 we compared 3 scenarios: a fulfilled EAG scenario; the EAG scenario without any gas; the EAG scenario with additional investments; and then compered the results. For imports and exports, the values from 2020 were used, only exports were allowed to exceed the specified value in order to reduce renewable energy curtailments. In the first scenario, 2.6 TWh of gas generation is needed to cover consumption despite the fulfilment of the EAG. In the case of a complete loss of gas supply, the second scenario shows that 0.9 TWh are taken over by oil production and another small part by others (70 GWh). The largest part of 1.5 TWh can just not be supplied. The third scenario shows the result with additional expansion (1.4 GW wind, 0.3 GW biomass and 1.66 GW pump storages), which increased generation from wind from 16.8 TWh to 20.1 TWh, and generation from (pump) hydro storages from 16.5 TWh to 18.6 TWh.

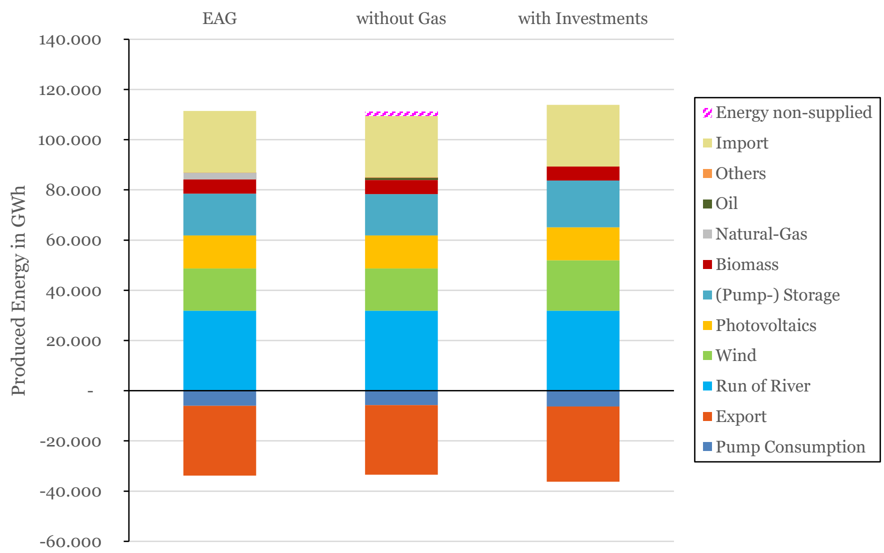

Figure 3-3: Comparison between the EAG scenario for 2030 on the left, in the middle there is the same scenario but without any gas and on the right with the additional option to invest

Monthly results for the 2030 scenario with additional investments enabled can be seen in Figure 3-4. Despite the fulfilment of the EAG and additional construction, imports must still be made in the months from October to March. The pumping consumption, which is smallest in July, although production is significantly higher than consumption in this month. This is due to the high inflows from meltwater at this time and the already high filling levels of the storages.

The wind generation, which is conspicuously small in January (see Discussion), December and January, but larger than average in February. Compared to 2022, production from biomass is no longer constant throughout the year due to the expansion. The addition of biomass can compensate for any missing energy in the winter months.

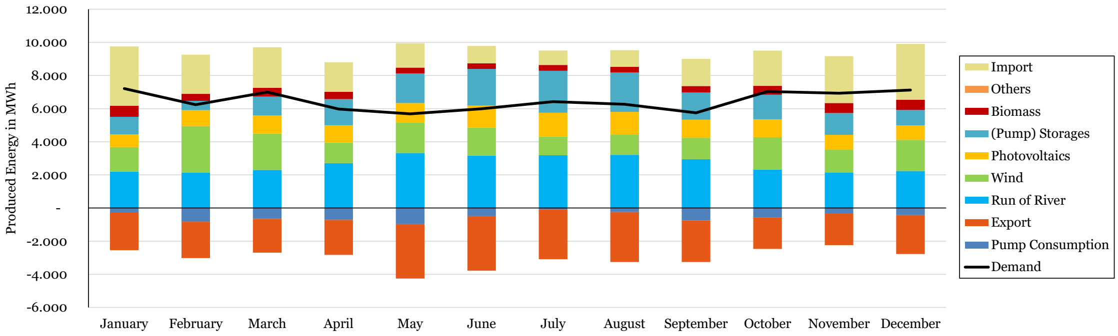

Figure 3-4: Generation and consumption by month for 2030 with the additional option to invest

4 DISCUSSION

The results of 2022 show that a sudden gas supply stop from Russia could potentially lead to 7.6 TWh of non-supplied energy (assuming everything else remains the same such as imports and exports staying the same). Of course, imports could be increased or exports reduced, but this energy would be missing in neighbouring countries, as they also generate a significant share of their generation from gas. To be able to capture this better in the future, it is necessary to integrate the Austrian model into a European model. Not included are the current gas storage levels, which could cushion the supply shortage in a first phase, but this would only be enough for a few months. In addition, other suppliers and, if necessary, significant savings measures would be needed to reduce gas consumption in other sectors that have not been analysed here.

The result of 3.2 shows that the Austrian electricity sector cannot easily do without gas even in 2030, despite achieving the EAG targets, as 3.9% of total demand is still generated with gas. In order to achieve the phase-out, further investments are unavoidable. In contrast to PV, the expansion of wind energy in particular brings higher yields in the winter months and at night, when gas-fired power plants would otherwise be necessary. Without this expansion, Austria will continue to be dependent on imports in the months of November to January. If one compares the generation from wind in the reference year 2020 with that of the same period from 2012 to 2021, it can be seen that it is significantly lower, especially in the months of November, December, and January. Under normal conditions, wind generation is highest in the winter months and lowest in midsummer.

In order to completely end the dependence on imports in the winter months, either a combination of wind, PV, and biomass would have to be added, or the excess energy from the summer would have to be transferred to the winter by storing it seasonally. This could be done using pumped storage hydropower plants or other storage technologies such as hydrogen storage. Hydrogen could also be used in industry for high-temperature processes and thus replace natural gas here as well.

If the electricity sector does indeed become completely free of fossil fuel combustion, this will bring new challenges elsewhere. Currently, the waste heat from these power plants is often used to supply district heating networks. In order to develop solutions for this problem as well, the heat sector could be implemented in the model in addition to electricity and hydrogen.

5 REFERENCES

[1] Nationalrat Österreich, *EAG*. Österreich: www.ris.bka.gv.at, 2021. Accessed: Jul. 25, 2022. [Online]. Available: https://www.parlament.gv.at/PAKT/VHG/XXVII/I/I_00733/fname_933183.pdf

[2] S. Wogrin, D. A. Tejada-Arango, R. Gaugl, T. Klatzer, and U. Bachhiesl, “LEGO: The open-source Low-carbon Expansion Generation Optimization model,” *SoftwareX*, vol. 19, p. 101141, Jul. 2022, doi: 10.1016/j.softx.2022.101141.

[3] SEPS, “Gridmap.” https://www.sepsas.sk/media/5365/central-europe-2021-12-31.png (accessed Aug. 09, 2022).

[4] APG, “Statisches Netzmodell APG-1,” *Austria Power Grid*. 2022. Accessed: Aug. 05, 2022. [Online]. Available: https://pb1-medien.apg.at/im/dl/pboxx-pixelboxx-8743/Statisches%20Netzmodell%20APG.pdf

[5] S. Pfenninger and I. Staffell, “Renewables.ninja.” https://www.renewables.ninja/ (accessed Aug. 05, 2022).

[6] C. Sejkora, L. Kühberger, F. Radner, A. Trattner, and T. Kienberger, “Exergy as criteria for efficient energy systems—a spatially resolved comparison of the current exergy consumption, the current useful exergy demand and renewable exergy potential,” *Energies (Basel)*, vol. 13, no. 4, 2020, doi: 10.3390/en13040843.

[7] R. Gaugl, T. Klatzer, U. Bachhiesl, S. Wogrin, and S. Jodl, “GIS-based optimization – achieving Austria’s 2030 wind energy target,” *Elektrotechnik und Informationstechnik*, vol. 138, no. 8, pp. 590–596, Dec. 2021, doi: 10.1007/s00502-021-00932-y.

[8] S. Wogrin, R. Gaugl, T. Klatzer, and U. Bachhiesl, “LEGO Module.” https://github.com/IEE-TUGraz/LEGO/ (accessed Jul. 25, 2022).

TECH4GREEN – DISRUPTIVE TECHNOLOGIES FOR A SUSTAINABLE TRANSFORMATION IN THE AUSTRIAN MATERIAL GOODS PRODUCTION

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** **Winner of the Young Scientist Award**

Abstract: While the manufacturing industry makes a significant contribution to Austria's economic performance, it is also responsible for a substantial share of the national GHG emissions. To address climate change, a sustainability transformation of the material goods production is necessary. Thus, this study investigates which technologies have the potential to facilitate a sustainable transformation of the Austrian manufacturing industry. A list of relevant technologies was created, based on a literature review, a meta-analysis of patent searches and two online surveys among technology and industry experts. These technologies were then assessed regarding their application potential in the industry and their contribution to energy and resource efficiency as well as climate protection. Logistics 4.0, manufacturing 4.0 and smart sensors optimize production or logistics processes, which in turn reduces energy consumption and GHG emissions. Carbon capture and utilization transforms CO_2 emissions into raw materials. Hydrogen made with renewable energy can substitute fossil energy sources in production. These technologies are widely applicable in the industry. Thus, they, among others, have the potential to facilitate sustainability transformation in the Austrian material goods production.

Keywords: disruptive technology, sustainability assessment, manufacture, material goods production, sustainability transformation

1 INTRODUCTION

With a share of around 18% of the gross domestic product, manufacturing makes a significant contribution to Austria's economic performance [1]. However, the Austrian industry and energy sectors cause about one third of national GHG emissions [2]. To tackle resulting issues like climate change and environmental degradation, a sustainability transformation is necessary [3]. In this context, the Austrian government programme 2020-2024 addresses the implementation of climate and environmental goals by industrial and manufacturing companies [4]. The effects of climate change are to be counteracted through more ecological, resource-conserving and climate friendly production in order to achieve climate neutrality by 2040 [4]. In order to reach the EU target of a 55% reduction in net GHG emissions by 2030, a reduction of GHG emissions by 61% of GHG emissions in the industrial sector compared to 2019 is necessary [5]. Therefore, comprehensive measures for a sustainability transformation of the material goods production must be taken.

Better technology is a key driver for achieving sustainability [6]. Thus, this study aims at providing a catalogue of technologies with the potential to facilitate a sustainable transformation of the Austrian manufacturing industry to guide future funding policy in a sustainable direction. For this, the following research questions were answered: Which disruptive technologies can contribute to sustainable material goods production? What are their sustainability impacts? Which of these technologies have great potential in Austrian material goods production?

2 MATERIALS AND METHODS

The following section describes the method applied in this study. First, disruptive technologies with relevance to the Austrian manufacturing industry were identified. Then, the sustainability impacts and application potential of these technologies were assessed.

2.1 Selection of Technologies

The disruptive technologies relevant to the Austrian manufacturing industry were identified through a broad literature review, a meta-analysis of patent searches and two online surveys among technology and industry experts. The literature search was primarily oriented towards studies on innovative technologies and disruptive innovations. The meta-analysis of patent searches focused on topics such as the fourth industrial revolution, machine learning, artificial intelligence and biobased industry in Austria. One survey was conducted among Austrian companies in the manufacturing sector. A second survey addressed Austrian research institutions. The participants were asked to what extent their own R&D activities are influenced by disruptive technologies or which disruptive technologies have had an effect in their respective sector.

A longlist of disruptive technologies relevant to the Austrian manufacturing industry was created. Selection criteria for this were e.g., type of innovation (radical or incremental), technology readiness level, disruptive character of the technology and how often the technology was mentioned in the expert surveys. Then, this longlist was narrowed down based on in which sector of the manufacturing industry these technologies can be applied and how this affects the industry.

2.2 Sustainability Assessment

The selected technologies were assessed with regard to their sustainability impacts. Based on the sustainability matrix by Wallner et al. [7], this study originally assessed a total of 27 impact categories in the social, economic and ecological sustainability dimension. However, this paper only elaborates the technologies' sustainability potential regarding the efficient use of resources and energy, as well as climate protection and the reduction of GHG emissions.

The sustainability assessment is based on the online survey results, a thorough literature review and the input from experts obtained in a workshop. Within the scope of the surveys, technology experts from manufacturing companies and research institutions were interviewed in order to assess, among other things, effects and impacts, current and future market diffusion as well as the need for development and action. Additionally, an extensive literature review was carried out for a complete assessment of the technology-related sustainability aspects. The sustainability assessment results were then presented to industry representatives and experts in a project workshop and the feedback from the participants was subsequently incorporated.

The sustainability impacts of the technologies in the respective impact categories were described qualitatively based on the survey results, literature review and workshop feedback. Subsequently, the extent of the impacts was rated on a scale from ‘strong positive effect on sustainability’ (+3) to ‘strong negative effect on sustainability’ (-3). Neutral ratings (0) were given if no sustainability effects occurred in the respective impact category. Additionally, the potential range of application of the selected technologies in the Austrian manufacturing industry was evaluated on a scale of one to five (see Table 2-1) based on the authors’ expertise and feedback from the workshop. The application range is a multiplying factor for the sustainability impacts. For example, a technology with very high positive sustainability impacts and a low range of application is exceeded by a technology with less positive sustainability impacts and a high range of application regarding their potential for a sustainable industry transformation.

Table 2-1: Scales for the assessment of potential range of application in the Austrian industry of the assessed technologies

Rating	Potential range of application
1	Technology only applicable to individual sectors and companies
2	Technology applicable for individual sectors in the majority of companies or for many sectors in a small number of companies
3	Technology applicable for all industries in a few companies or for a few industries in all companies
4	Technology applicable for all industries in some companies or for some industries in all companies
5	Technology applicable to all industries and a majority of companies

3 RESULTS

This study assessed a total of 27 impact categories in three different dimensions of sustainability. However, this paper only elaborates the results for the two impact categories ‘efficient use of energy and resources’ as well as ‘climate protection and the reduction of GHG emissions’.

3.1 Disruptive Technologies relevant to the Austrian Manufacturing Industry

Based on the survey results, literature review and meta-analysis of patent research, a short-list of 26 disruptive technologies relevant to the Austrian manufacturing industry was created. For the purpose of this paper, this list was further narrowed down to twelve technologies. Table 3-1 shows these technologies and a short technology description. Additionally, the potential range of application in the Austrian manufacturing industry is given. A high application potential equals a rating of 5 and a low application potential equals a rating of 1.

Table 3-1: List of the selected disruptive technologies and their potential range of application in the Austrian manufacturing industry

Technology	Technology description	Range of Application
Artificial intelligence (AI)	The ability of machines to perform tasks autonomously and to react adaptively to new situations [8]	4
Augmented reality	Assembly instructions or manufacturing steps can be displayed directly on glasses or visors [9]	3
Carbon capture and utilization (CCU)	Carbon dioxide is extracted from air or exhaust gas and used as a raw material for different applications [10]	3
Chemical recycling	Waste is chemically recycled into basic chemicals, e.g., through pyrolysis, gasification or liquefaction [11]	2
Electric arc furnace	Can replace high-temperature heat processes in metal processing that are difficult to electrify [12]	1
Enzymatic waste processing	Plastic waste is enzymatically processed in order to extract basic chemicals or to degrade the waste accordingly [13]	2
Hydrogen	The hydrogen produced through electrolysis of water can be used as fuel, energy carrier and feedstock [10]	5
Hydrothermal liquefaction (HTL)	A thermal process in which a product similar to crude oil is obtained from biomass [14]	2
Logistics 4.0	Driverless road and rail vehicles for the transport of goods with automated loading, reloading and unloading [10]	5
Manufacturing 4.0	The smart automation of manufacturing processes and cloud manufacturing [15]	3
Smart sensors	Smart sensors, which are able to independently re-evaluate the measured values [16]	4
Virtual reality	The virtual environment is represented in its entirety as far as possible and tasks are completed completely virtually [17]	3

3.2 Ecological Sustainability Impacts

Figure 3-1 shows the technologies' aggregated ecological sustainability impacts on energy and resource efficiency as well as climate protection in addition to their application potential in the industry. Technologies with a high application potential and a high sustainability impact (top right quadrant) very positively contribute to sustainable manufacturing. Technologies with a high sustainability impact and a low application potential (bottom right quadrant) have little positive contribution to sustainability. Low sustainability impact and low application potential (bottom left quadrant) as well as low sustainability and high application potential (top left quadrant) result in a negative sustainability contribution. Logistics 4.0 and smart sensors have the highest contribution to energy and resource efficiency and climate protection. Hydrogen, CCU, manufacturing 4.0 and virtual reality also very positively contribute to a sustainable industry. Chemical recycling, hydrothermal liquefaction, enzymatic waste processing and electric arc furnace have a slight positive contribution to ecological sustainability. While augmented reality does not have any effect on ecological sustainability, artificial intelligence has a negative ecological sustainability contribution.

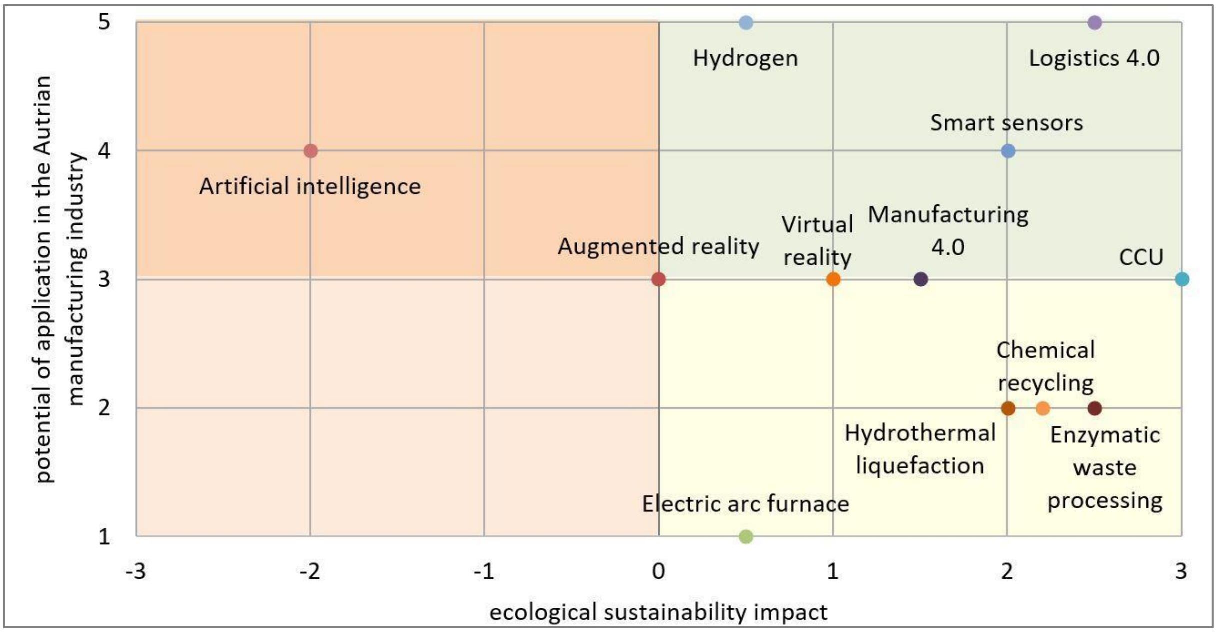

Figure 3-1: The technologies' contribution to ecological sustainability as a result of their ecological sustainability impact and their application potential in the Austrian manufacturing industry

Artificial intelligence can improve efficiency of supply chains, heating, cooling systems and energy consumption [18]. Additionally, it can prioritize renewable energies in energy consumption, which reduces energy related GHG emissions [18]. However, the need for high computing power leads to high energy consumption (e.g., cooling, lighting) [18]. Thus, artificial intelligence has a negative ecological sustainability effect. This technology is applicable in all sectors and in many companies of material goods production.

Augmented reality has no noticeable effects on energy and resource efficiency or climate protection. In material goods production, augmented reality is particularly relevant for assembly and product development and therefore has a medium application potential in the industry.

CCU delays the release of CO_2 emissions and thus significantly contributes to climate protection [19]. In the case of fossil energy sources it delays carbon emissions, in the case of biogenic sources it represents a further use of biogenic resources [19]. The captured CO_2 can then be used as a secondary raw material [10]. In the case of carbon capture utilization and storage (CCUS), the CO_2 can be used to create building materials (e.g., cement, concrete) and is thus permanently bound and cannot enter the atmosphere [20]. CCU is applicable in most manufacturing industries, but rather in larger companies.

Through chemical recycling, plastic waste can be used as secondary raw material. This leads to a decarbonization of the plastic industry as less fossil raw materials are used for plastic production and thus GHG emissions are reduced [11]. Chemical recycling is particularly relevant for the chemical industry and the textile industry (especially synthetic fibre production). An application is conceivable for all company sizes.

Despite its high electricity demand, steel production from scrap in electric arc furnaces results in substantially less GHG emissions compared to blast furnace steel production [21]. In addition to iron scrap, sponge iron from direct reduction of iron ores can also be processed in electric arc furnaces, which reduces the need for blast furnace steel production [22]. These technologies are only relevant for steel production and metal processing, and especially for large companies.

Still, a large part of plastic waste ends up being landfilled, which increases GHG emissions [23]. Enzymatic recycling can be used to break down mixed plastic waste, which allows for the recycling of materials which are currently not recycled [13]. This way, raw material cycles can be closed and the production of primary plastic is substituted. Additionally, GHG emissions are reduced, as plastic recycling causes less emissions than primary plastic production [13]. This technology is only relevant for the chemical industry, especially the plastics industry.

Hydrogen can substitute fossil energy sources and thus reduce GHG emissions, provided that the electricity for its production comes from renewable sources [24]. In addition, production peaks, caused for example by the weather dependency of renewable electricity generation, can be balanced out by using the surplus electricity to produce hydrogen (power to gas) [25]. This hydrogen can later be converted into electrical energy if needed [25]. As an alternative energy source, hydrogen is applicable in all sectors and companies of material goods production. For a contribution to climate protection, however, hydrogen production with renewable energy, which must be available in sufficient quantities for this purpose, is necessary [25].

Hydrothermal liquefaction uses biogenic waste as raw material to produce a biological crude oil substitute [26]. This substitute has twice the energy density of pyrolysis oil [27] and can avoid GHG emissions by substituting fossil crude oil [28]. Furthermore, the treatment of biogenic wastes instead of landfilling prevents methane emissions [26]. This technology is mainly relevant for refineries, energy production and waste management, and thus has a low application potential in Austrian material goods production.

Logistics 4.0 allows for the optimization of routes and prevents empty runs of vehicles. Therefore, fuel usage is reduced, which avoids GHG emissions [29]. Autonomous logistics additionally reduces emissions through anticipatory driving [29]. Logistics 4.0 is applicable in all industries and companies that ship goods or receive deliveries. Therefore, it has a very high application potential in the Austrian manufacturing industry.

With manufacturing 4.0, material and energy flows can be monitored simultaneously and coordinated with each other [30]. This way, synergy effects increase resource and energy efficiency, which reduces GHG emissions [30]. Manufacturing 4.0 is applicable in most companies in the manufacturing industry.

Smart sensors facilitate process optimization and reduce energy consumption (e.g., for heating, cooling, lighting) [31]. This reduces GHG emissions [31]. As part of Industry 4.0, smart sensors can be used in many areas of material goods production for process monitoring and optimization.

Virtual reality allows for the digital visualization of product ideas and changes in product design before a physical prototype is manufactured [32]. Thus, raw material and resources are saved [32]. Virtual meetings and events eliminate the need for participants to travel, thus avoiding GHG emissions [33]. Virtual reality is relevant for a few industrial sectors, but for many companies in these sectors, especially in manufacturing, architecture or product development.

4 DISCUSSION AND CONCLUSION

The identified technologies relevant to the Austrian manufacturing industry are artificial intelligence, augmented reality, CCU, chemical recycling, electric arc furnace, enzymatic waste processing, hydrogen, hydrothermal liquefaction, logistics 4.0, manufacture 4.0, smart sensors and virtual reality. A technology's contribution to a sustainable material goods production does not only depend on its sustainability impact, but also on the range of its application in the industry. Technologies with a high positive sustainability impact and a high application potential in sectors which are of high significance for sustainable transition have a higher contribution to sustainable manufacturing. Because of their high applicability in the industry and their sustainability impacts, logistics 4.0, smart sensors and hydrogen show the greatest potential for a sustainable material goods production. The sustainability potential of logistics 4.0 and smart sensors lies in the increased efficiency of processes and the resulting reduction in energy and resource consumption and emissions [29]–[31]. Hydrogen produced with renewable energy can substitute fossil based energy for the industry and the resulting emissions [24]. However, a prerequisite for this is a sufficient supply of renewable energy [25]. These technologies are of high significance for decarbonisation of energy systems and reduction of transport-related emissions.

CCU, manufacturing 4.0 and virtual reality strongly contribute to sustainable manufacturing as well. CCU captures CO_2 emissions [19] and prevents their release into the atmosphere when they are converted in form of CCUS to long-term stable compounds [20], which substantially contributes to the decarbonization of the industry. Manufacturing 4.0 increases process efficiency and thus reduces industry GHG emissions [30] which is of high significance for reaching the emission reduction goals. Virtual reality can be used for digital and thus material-saving product development [32]. Virtual events reduce emissions by avoiding travelling activities [33] which can significantly help to reduce traffic and the induced GHG-emissions.

Chemical recycling, enzymatic waste processing, hydrothermal liquefaction and electric arc furnaces have a slight positive sustainability effect. Chemical recycling and enzymatic waste processing close raw material cycles and thus avoid GHG from primary material production [11], [13]. Hydrothermal liquefaction provides a biobased substitute for fossil crude oil [26]. Electric arc furnaces are a less emission-intensive way of steel processing and facilitates metal recycling [21]. The significance of these technologies lies especially in their contribution to realize a circular economy. Augmented reality does not contribute to ecological sustainability because its focus lies on visualisation of products and processes [32]. Due to its high energy demand [18], artificial intelligence has a negative sustainability contribution. Harvesting the potential of these technologies with a positive sustainability contribution and implementing them into the Austrian material goods production accelerates sustainability transformation.

5 REFERENCES

[1] WKO, "Statistische Daten für Industrie und Sachgüterproduktion", 2020. [online document]. Available: https://www.wko.at/service/zahlen-daten-fakten/industrie-sachgueterproduktion.html [Accessed Jul. 05, 2021].

[2] UBA, "Klimaschutzbericht 2021", 2021. [online document]. Available: https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0776.pdf [Accessed Mar. 15, 2021].

[3] W. C. Clark, "A Transition toward Sustainability", *Ecology Law Quarterly*, vol. 27, pp. 1021-1076, 2001.

[4] Bundeskanzleramt Österreich, "Aus Verantwortung für Österreich. Regierungsprogramm 2020–2024". 2020. [online document]. Available: https://www.bundeskanzleramt.gv.at/dam/jcr:7b9e6755-2115-440c-b2ec-cbf64a931aa8/RegProgramm-lang.pdf [Accessed: Feb. 13, 2022].

[5] C. Diendorfer et al., "Klimaneutralität Österreichs bis 2040. Beitrag der Österreichischen Industrie". 2021. [online document]. Available: https://www.bmk.gv.at/dam/jcr:0ac604d1-7928-492f-991a-4845dce78c27/Begleitstudie_Endbericht.pdf [Accessed: Mar. 10, 2022].

[6] B. Allenby, "Supporting environmental quality: Developing an infrastructure for design", *Environmental Quality Management*, vol. 2, no. 3, pp. 303–308, 1993.

[7] H. P. Wallner, K. Schauer, A. Windsperger, H. Strebel, E. Schwarz, and B. Lenz, *Projekt-Innovations-Matrix. Ein Instrument für die integrierte nachhaltige Entwicklung von Regionen*. s.l.: BMVIT, Amt der Steiermärkischen Landesregierung, Amt der Niederösterreichischen Landesregierung, WKO – WIFI Österreich, 2002.

[8] O. Mulhern, "Can AI Help Achieve Environmental Sustainability?". *Earth.org*, 2021. [Online]. Available: https://earth.org/data_visualization/ai-can-it-help-achieve-environmental-sustainable/ [Accessed Jun. 01, 2021].

[9] P. Stelzer, "ASSIST 4.0 - Service Avatar: Eine neue Dienstleistungsära beginnt", *Produktion der Zukunft*, s.a. [Online]. Available: https://produktionderzukunft.at/de/projekte/assist-40-service-avatar-eine-neue-dienstleistungsaera-beginnt.php [Accessed Feb. 01, 2022].

[10] European Commission Directorate General for Research and Innovation, *100 radical innovation breakthroughs for the future*. Brussels: Publications Office, [online document], 2019. Available: https://data.europa.eu/doi/10.2777/563770 [Accessed: Jul. 13, 2022].

[11] J. Vogel, F. Krüger, and M. Fabian, *Chemisches Recycling*. Dresden: Umweltbundesamt, 2020.

[12] R. Valentini, V. Colla, T. A. Branca, A. Osta, and S. Manthey, "Innovation and Sustainability in Electric Arc Furnace Steel Production", in *Récents Progrès en Génie des Procédés*, Paris: Société française de génie des procédés diff. Lavoisier-technique et documentation, 2007.

[13] A. Singh et al., "Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly(ethylene terephthalate)", *Joule*, vol. 5, no. 9, pp. 2479–2503, 2021.

[14] S. Guran, "Sustainable Waste-to-Energy Technologies: Hydrothermal Liquefaction", in *Sustainable Food Waste-To-energy Systems*, Elsevier, 2018, pp. 159–175.

[15] M. Lasnig et al., *Kenntnisstand und Einstellung zur digitalen Transformation durch Industrie 4.0 und neue Geschäftsmodelle in österreichischen Unternehmen*, Band 2. Vienna: BMVIT, 2016.

[16] J. M. Chabas, C. Gnanasambandam, S. Gupte, and M. Mahdavian,"New demand, new markets: What edge computing means for hardware companies". *McKinsey & Company*, 2018. [Online]. Available:

https://www.mckinsey.com/~/media/McKinsey/Industries/Technology%20Media%20and%20Telecommunications/High%20Tech/Our%20Insights/New%20demand%20new%20markets%20What%20edge%20computing%20means%20for%20hardware%20companies/New-demand-new-markets-What-edge-computing-means.pdf [Accessed Feb. 01, 2022].

[17] Y. Ménière, J. Valdés, and I. Rudyk, *Patents and the fourth industrial revolution: The inventions behind digital transformation*. s.l.: European Patent Office, 2017.

[18] F. Rohde et al., *Nachhaltigkeitskriterien für künstliche Intelligenz. Entwicklung eines Kriterien- und Indikatorensets für die Nachhaltigkeitsbewertung von KI-Systemen entlang des Lebenszyklus*. Berlin: IÖW, 2021.

[19] P. Gabrielli, M. Gazzani, and M. Mazzotti, "The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO 2 Emissions Chemical Industry", *Industrial & Engineering Chemistry Research*, vol. 59, no. 15, pp. 7033–7045, 2020.

[20] International Energy Agency, “About CCUS”, 2021. [Online]. Available: https://www.iea.org/reports/about-ccus [Accessed Sep. 28, 2022].

[21] M. Aichinger, „Technologievergleich von Elektrostahlerzeugungsverfahren“, Master of Science Thesis, Montanuniversität Leoben, Leoben, 2015.

[22] Stahlinstitut VDEh, "Roheisen- und Rohstahlerzeugung", Stahlinstitut VDEh, s.a. [Online]. Available: https://vdeh.de/stahltechnologie/stahlerzeugung/ [Accessed Feb. 20, 2022].

[23] A. Amobonye, P. Bhagwat, S. Singh, and S. Pillai, "Plastic biodegradation: Frontline microbes and their enzymes", *Science of The Total Environment*, vol. 759, p. 143536, 2021.

[24] Energy Innovation Austria, "Grüner Wasserstoff und Brennstoffzelle Schlüsseltechnologien auf dem Weg zur Klimaneutralität", *Energy Innovation Austria*, 2020. [Online]. Available: https://www.energy-innovation-austria.at/article/gruener-wasserstoff-und-brennstoffzelle/ [Accessed Feb. 21, 2022].

[25] M. Kruse and J. Wedemeier, "Potenzial grüner Wasserstoff: langer Weg der Entwicklung, kurze Zeit bis zur Umsetzung", *Wirtschaftsdienst*, vol. 101, no. 1, pp. 26–32, 2021.

[26] K. K. Ramasamy et al., *Hydrothermal Liquefaction: Path to Sustainable Aviation Fuel*. November 17–19, 2020, Virtual Workshop in ZOOM Platform. Alexandria, VA: Pacific Northwest National Laboratory, 2020.

[27] S. Bacher, “Hydrothermale Biomasseverflüssigung”, Master of Science Thesis, Montanuniversität Leoben, Leoben, 2016.

[28] C. U. Jensen, J. K. Rodriguez Guerrero, S. Karatzos, G. Olofsson, and S. B. Iversen, “Fundamentals of HydrofactionTM: Renewable crude oil from woody biomass”, *Biomass Conversion & Biorefinery*, vol. 7, no. 4, pp. 495–509, 2017.

[29] Vereinigung der Bayerischen Wirtschaft e. V, "Klima 2030. Nachhaltige Innovationen", *Vereinigung der Bayerischen Wirtschaft*, 2020 [Online]. Available: https://www.vbw-bayern.de/Redaktion/Frei-zugaengliche-Medien/Abteilungen-GS/Wirtschaftspolitik/2020/Downloads/ZKR_Klima-2030/vbw-ZKR-2020_Klima-2030_Studie_new.pdf [Accessed Feb. 4, 2022].

[30] Plattform Industrie 4.0, "Nachhaltige Produktion: Mit Industrie 4.0 die Ökologische Transformation aktiv gestalten". Bundesministerium für Wirtschaft und Energie (BMWi), 2020. [Online]. Available: https://www.plattform-

i40.de/IP/Redaktion/DE/Downloads/Publikation/Nachhaltige-Produktion.pdf?__blob=publicationFile&v=4 [Accessed Feb. 3, 2022].

[31] E. Roobol, "Können Überwachungskameras und Sensoren dazu beitragen, eine nachhaltigere Welt zu kreieren?", *Secure Insights*, 2019. [Online]. Available: https://www.axis.com/blog/secure-insights-de/kameras-und-sensoren-tragen-zu-nachhaltigeren-welt-bei/ [Accessed Feb. 1, 2022].

[32] Industrieanzeiger, "Augmented- und Virtual Reality machen Produktion greifbar, bevor sie entsteht", *Industrieanzeiger*, 2020. [Online]. Available: https://industrieanzeiger.industrie.de/management/augmented-und-virtual-reality-machen-produktion-greifbar-bevor-sie-entsteht/ [Accessed Feb. 1, 2022].

[33] M. Zwettler, "Wie Virtual Reality Zeit, Geld und CO_2 spart", *Konstruktionspraxis*, 2020. [Online]. Available: https://www.konstruktionspraxis.vogel.de/wie-virtual-reality-zeit-geld-und-co2-spart-a-951869/ [Accessed Feb. 1, 2022].

IV. Presentations: Industrial Process Optimisation

GANYMED – THE DEVELOPMENT OF AN INDUSTRIAL LOAD PROFILE GENERATION SOFTWARE

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Abstract: The rising volatility of industrial energy systems bears new challenges for all energy related research endeavours. The transition of physical energy systems into the digital world can bring forth new solutions by swiftly evaluating trends and changes and their implications. One of these solutions lies in the generation of synthetic industrial load profiles, which majorly support the strategic decision making for energy suppliers, grid operators and industrial plants itself when implementing new technologies or renewable energies at industrial sites. However, due to the heterogeneity of the industrial landscape in terms of processes and production route structures, there are still solutions missing for depicting all industries in a standardised and user-friendly way. We therefore developed the simulation software *Ganymed* and implemented methodologies and data bases for generating the LPs of user-defined production routes as well as for synthetic industrial sites. These methodologies consist of the time based simulation paradigm of discrete event simulation for evaluating the energy intensive industrial subsectors and of stochastic algorithms handling open accessibly databases for analysing non-energy intensive subsectors. These approaches are encapsulated within the software framework and are controllable via a graphic user interface.

Keywords: Industry; Load Profile; Simulation; Energy System; Generation; Software; Interface; Ganymed

1 INTRODUCTION

Rapidly changing environmental and socio-economic influences confront the modern energy system with significant challenges. However, the rising digitalisation offers novel solutions for solving these problems. Energy system models play a vital role within this topic, especially in terms of assessing external impacts and developing optimisation measures.

The industry acts as a major part of the global energy system. In Europe, the industrial landscape is accountable for around 20% of the gross domestic energy consumption [1]. However, compared to other energy consuming sectors like residential and mobility, assessments and models for the industrial sector exhibit to be more challenging in their development due to the industry's heterogeneous nature in process and product variety [2]. Therefore, there are still vast open research areas to cover in energy research activities. One of these areas is the development of approaches to depict the dynamic demand and generation behaviour of industrial sites [3]. Because of major technological advancements in the recent and upcoming years and the increasing implementation of renewable energies, knowledge of the dynamic energy demand of consumers offers important insights for grid operators, energy suppliers and industries themselves [4]. We therefore present *Ganymed*, a developed software for generating synthetic load profiles (LPs) of industrial sites. This software is, to our knowledge, the first of its kind for the industrial sector.

2 DEVELOPING *GANYMED*

2.1 Overall Industry Classification

To develop an approach covering the entire industry, the sector needs to be classified in a standardised way. We conducted this classification via researching certain characteristics of the industrial energy system e.g. energy consumption, gross value added, number of employees, applied processes, products etc. According to the EU commission, the industrial sectors can be structured in energy intensive and non-energy intensive, of which the first one – as part of the primary industry – "exhibits a limited range of varying production processes and principles" [2]. Figure 1 shows the share of primary energy consumption and distribution

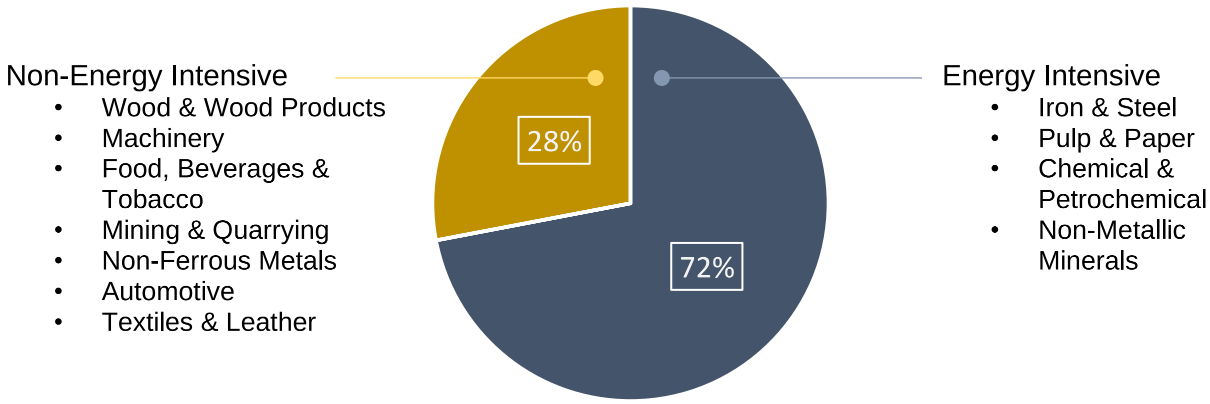

Figure 1: Shares of primary energy consumption 2019 of industrial subsectors in Austria

by subsectors of these two groups [5]. For the latter we apply the classification according to IEA [6] which is the basis for our further investigations.

2.2 Establishing Methodologies

As our main research goal is to generate LPs for single industrial plants, we developed and applied different methodologies based on the subsector classification above. We utilised the programming language Python to create a software environment combined with a graphical user interface (GUI). By developing *Ganymed* we embedded these simulation methodologies into this environment. Here, we want to give a short overview over the approaches for generating LPs for the energy intensive and non-energy intensive subsectors.

2.2.1 Load-profiles for Energy Intensive Subsectors

As we declared above, because of the limited process and product variety of energy intensive subsectors, information and data on process level can be gathered through literature research and measurements in a straightforward way. We applied a bottom-up approach for handling this data and generating LPs from process to plant level. The approach is based upon the paradigms of object oriented programming (OOP) and discrete event simulation (DES) [7].

Figure 2 shows the developed methodology for energy intensive subsector. We published a detailed description of this work in Binderbauer et al. [2].

When the user creates a new process step as e.g. a pulp digester, etc. on the GUI, Ganymed searches through its database for the according process information (1). The

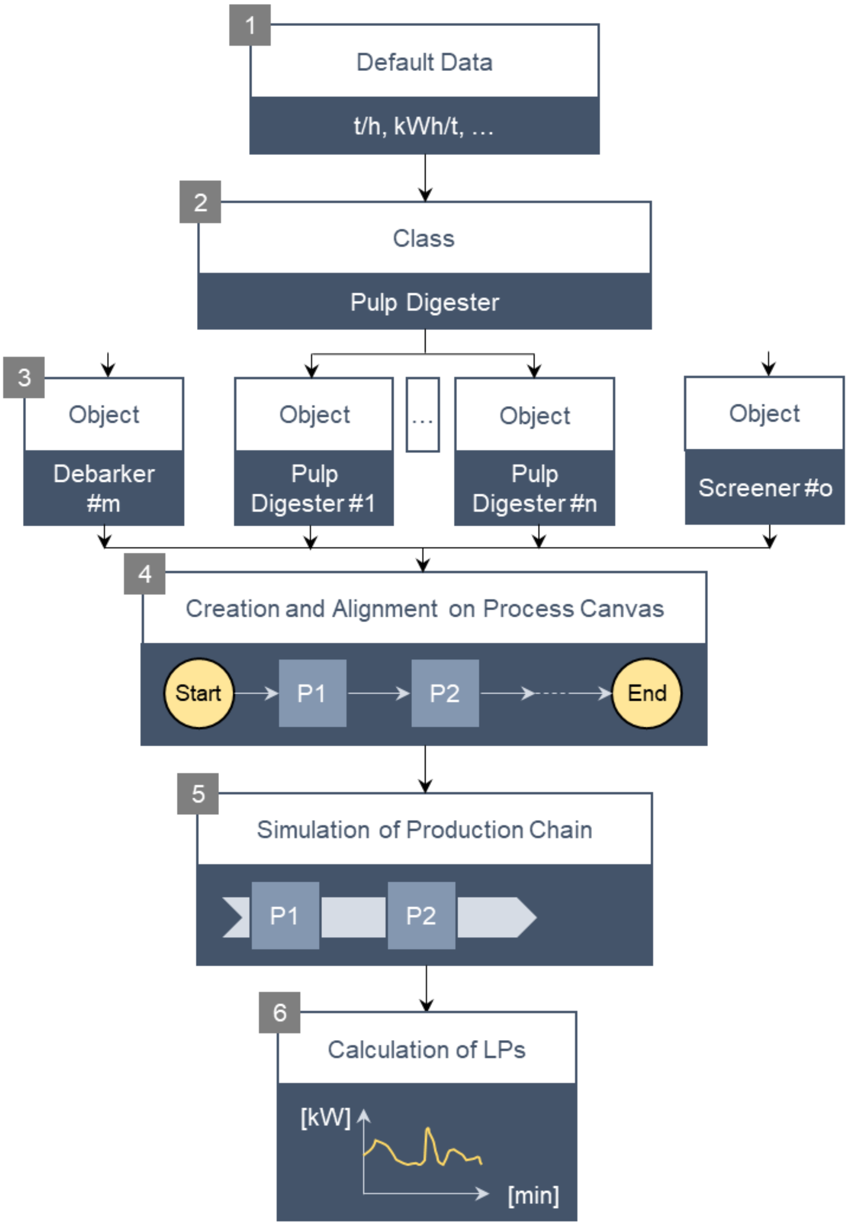

Figure 2: Methodology for generating industrial LPs for energy intensive industries

resulting dataset contains information on the process' capacity, operating times, single energy consumption times series or specific energy consumption operating type etc. An overall process class (2) contains functions, which determine how the process is handled in the GUI and during simulation. With this standard process, various industrial processes with similar functionalities can be depicted in an efficient manner. By receiving data from the overall database, process objects are created (3). The processes' properties contain the default data and can be overwritten independently by the user. In a next step, the user aligns all considered processes in the GUI to meet the desired overall production chain via drag and drop (4). The user then connects the processes from a defined start and end object by connecting all involved objects via product material streams. Alternatively, the user can "load in" predefined production chain templates e.g. integrated pulp & paper production via Kraft process etc., which already contain a predesigned production route. After conducting the desired adaptions, the user then initiates the simulation (5). Here, we utilised the approach of DES, which we adapted to meet industrial characteristics. Via DES, a predefined amount of discrete batches (e.g. tonnes of pulp or steel) is created at the start object. These batches are then send through the aligned production route in a sequential order. When a batch is operated in a process, the sequence before the simulation is halted until the process finished the operation of the current batch. During this stop-and-go processing, single process energy demand pattern at certain times during simulation. After all batches are finished, these single energy demand profiles are summed up to generate the resulting production route LP (6).

2.2.2 Load profiles for Non-Energy Intensive Subsectors

Even though, the non-energy intensive subsectors make up for less than a third of primary energy consumption in industry (Figure 1), they exceed the energy intensive subsectors in regard to number of employees, added value and varying products [8]. Thus, these subsectors are to be involved in energy system and LP analyses as well. However, because of the high number of different processes and production routes a sole bottom-up approach for generating LPs like in section 2.2.1 will reach its limits [9]. This is because the required database will be far greater compared to the energy intensive subsectors, regardless

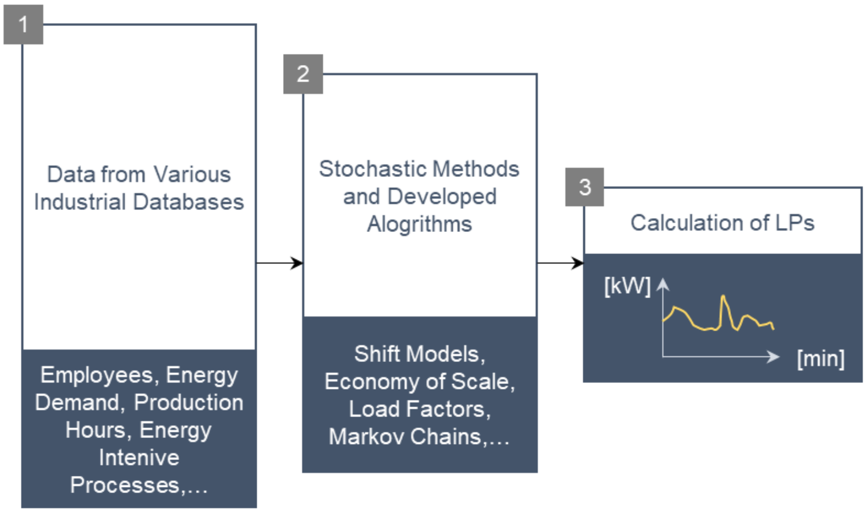

Figure 3: Methodology for generating LPs for non-energy intensive subsectors

if the information can be acquired in a satisfactory way. We therefore developed a more top-down methodology for depicting these subsectors, which is shown in Figure 3.

We utilized various databases for revealing correlations between number of employees, annual and product specific energy demand, production hours etc. of single plants and their corresponding LPs (1). The databases are the Industrial Assessment Center database [10], Herold Business database [11] and Useful Energy Analysis by Statistics Austria [12]. Based on the data from (1) we investigated various correlations e.g. between shift models and LPs. [13]. In (2) we developed algorithms to predict necessary target values based upon these correlations e.g. stochastically determining possible shift models for defined number of employees or assessing the specific energy consumption based upon production capacity and the microeconomic effect of economy of scale. Information of known most energy intensive processes in these subsectors are handled within dynamic Markov chains and make up for the peak demand in the LPs. These LPs are then further scaled by utilizing load factors based upon the data from the databases (3). We described the developed approach more in detail in our recent publication [14].

2.3 Combination of all Industrial Subsectors within *Ganymed*

We created the software environment *Ganymed* as a framework for implementing all developed approaches for generating industrial LPs. From a programming point of view, the architecture of *Ganymed* is divided into several scripts, which are handled by the core script "Main Code", see Figure 4. The "Main Code" also contains a master class, which operates the GUI and the remaining software environment.

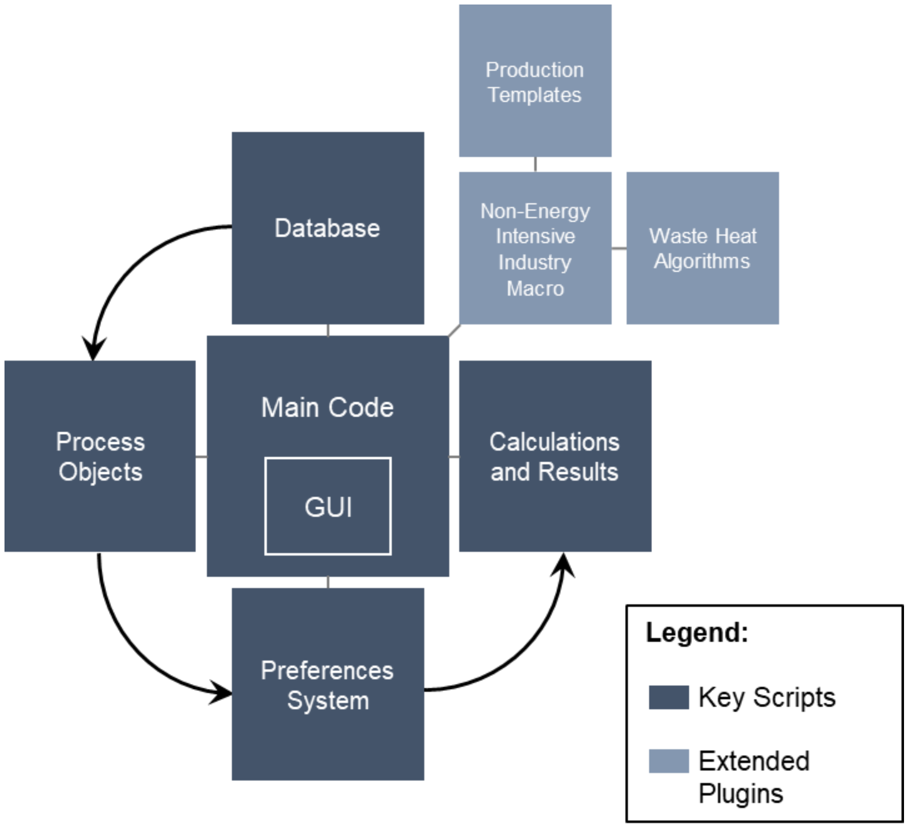

Figure 4: Ganymed's architecture and implementation of key scripts and extended plugins

All other classes in *Ganymed* inherit from this master class and are encapsulated from direct access of the user. Because the software is built around the depiction of energy intensive subsectors, the corresponding scripts are the main pillars of *Ganymed's* architecture (key scripts in Figure 4). Within the process canvas in the GUI, processes are created, aligned and adapted by the user. The black arrows in Figure 4 indicate the chain of effects which is also depicted in Figure 2.

The implementation of non-energy intensive subsectors was achieved by developing a so-called "Industry Macro". We designed this macro to act as a process, however including the full range of approaches for depicting non-energy intensive processes as outlined above. Through this, the macro can still be part in the process canvas and be included in the simulation without the need of introducing major changes into the programme's architecture. Here, the Industry Macro is an external script, which is loaded into *Ganymed* on user's requirement. A similarly handled script is the data on production route designs ("Production Templates").

In an upcoming study, the generating of waste heat profiles for both energy intensive and non-energy intensive sectors will be made possible within *Ganymed*. This will also act as an external script.

2.4 Single Process depiction on the Process Canvas

The creation and configuration of processes on process canvas takes an important role within *Ganymed*. Figure 5 shows a visual representation of an exemplary process on the canvas as well all process dependent preferences, to be freely adjusted by the user. The square which depicts 1 of *n* process objects can be moved freely by the user via drag and drop. The material in- and outflows are indicated by thin arrows, which are to be aligned by the user or predefined in the production route templates. These material routes pass the created batches from DES from on process to another.

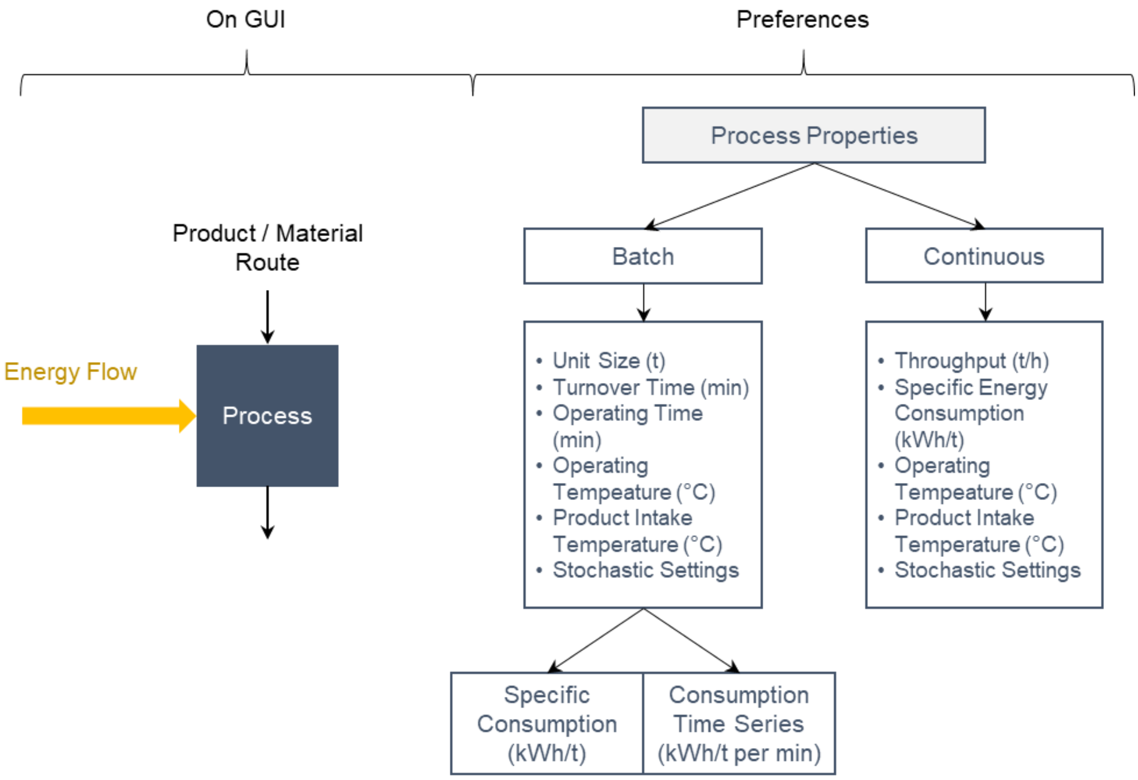

Figure 5: Process representation on GUI and accompanying properties

Also the visual representation of energy flows of different implemented energy carriers in and out of the process are to be established in the same way. Additionally, the user can create movable system boundaries on canvas. With these, the LPs of singular parts of the overall production chain can be depicted without the need of changing the whole route. For energy system research these boundaries can be applied for evaluating LPs on different systemic levels, e.g. plant border, final energy, useful energy, etc. The eligible energy flows have to intersect the system boundary accordingly.

Within the script “Process Objects” (see Figure 4), a template of the shown process properties is created and filled with the respective default process data from the database. These datasets are stored in arrays. *Ganymed* classifies processes in regard to their operating characteristics in batch and continuous working processes. The specific properties are defined according to this classification. Furthermore, batch working processes can either apply specific energy consumption or energy consumption time series (e.g. singular processes’ LPs). The latter can be imported via .CSV-sheets (see Figure 5).

The process properties of throughput, unit size, turnover time, operating times and energy consumption directly correspond to DES and the generation of LPs. Operating temperature and product intake temperature are datasets for generating waste heat profiles and are handled by waste heat algorithms in *Ganymed*.

2.5 Production route depiction on the Process Canvas and *Ganymed*'s GUI

The interface between the user and the main code is established through a GUI. The script is based upon the Python library Tkinter [15]. The GUI is separated in three compartments: Menu, process canvas and calculation & results sheet.

Figure 6 shows the process canvas in *Ganymed*. In the "General" section the user can initiate the simulation, save, open current files or create a new process canvas. Also, the global settings like overall stochastic fluctuations, labelling of flows, overall production capacity, etc. can be adapted throughout this menu.

The menu for "Set & System Objects" enables the creation of all start and end points for the production route. Furthermore, through this menu new energy carriers and material flows can be established. Also, system boundaries and the non-energy intensive industry macro can be created on canvas.

All single processes can be accessed through the "Process menu". Here, the processes are divided into mechanical, thermal, chemical and special (e.g. CHP, buffer points, etc.) processes.

The "Templates menu" allows the user to insert the already mentioned predefined production routes for Pulp & Paper, Iron & Steel, Chemical or Non-metallic Minerals industries.

When a mentioned process or production route is chosen, the corresponding visual representation of the objects are created on the process canvas. Each process consists of the process' name, continuous/batch symbol, consecutive object number, preferences' button and four anchor points, see Figure 7. Through clicking on the anchor points, material and energy flows to other processes and busbars can be established. By clicking on the process square itself, the process can be moved freely on the canvas via drag and drop.

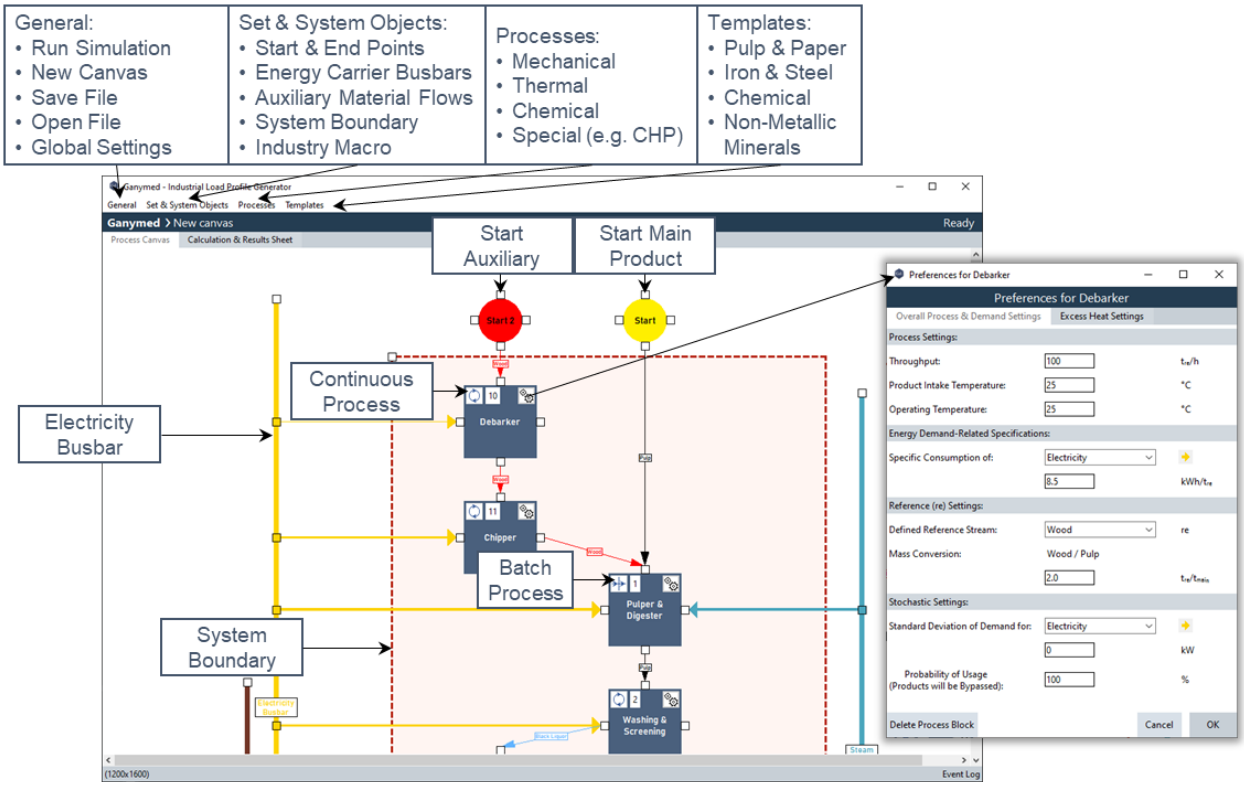

Figure 6: Ganymed's GUI: Process canvas and preferences of process

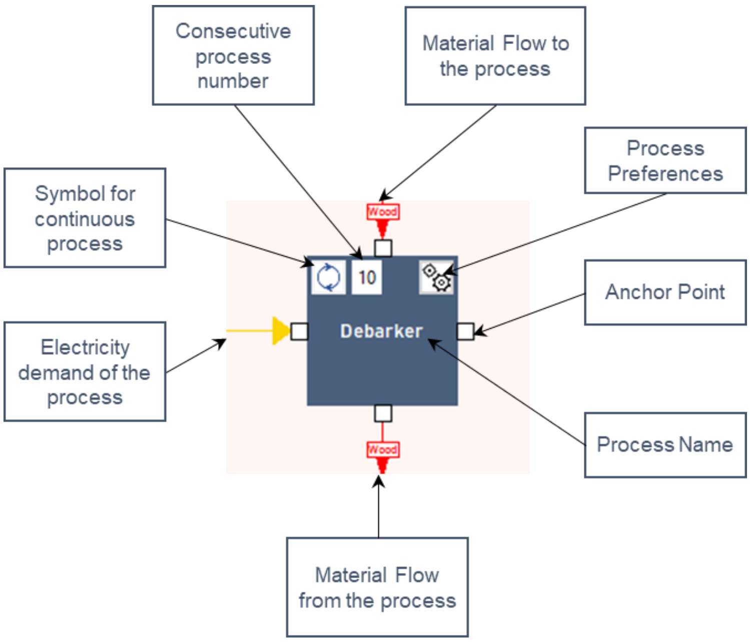

Figure 7: Visual representation of a process on process canvas

After the simulation is finished, the user can switch to the calculation & results sheet to view the generated LPs and export them, see Figure 8. On this frame, the user can also select and cut out representative parts of the LP to generate a weekly LP. The export is done via .CSV-format. On this sheet, the user also can view the evaluations on waste heat profiles and longest queue lengths of batches for single processes.

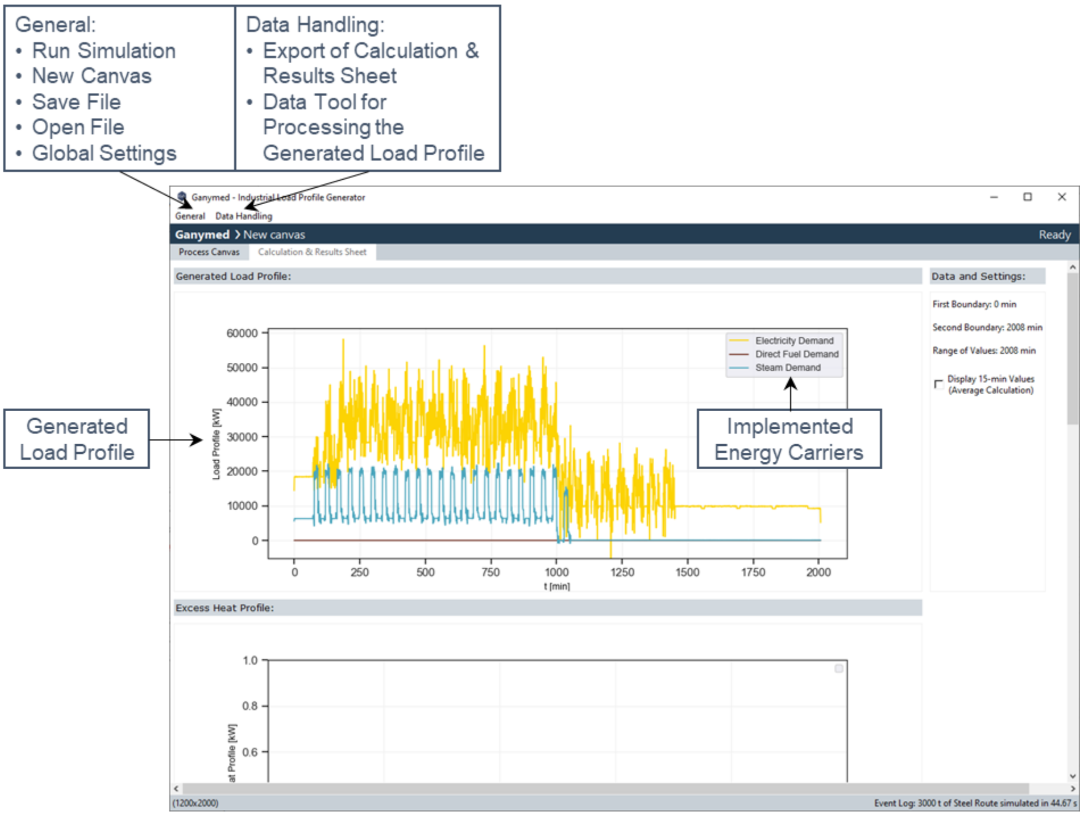

Figure 8: Ganymed's GUI: Calculation & results sheet

3 CONCLUSION

By utilising the idea of object oriented programming e.g. encapsulation, inheritance, classes and objects, industrial processes can be handled systemically adequate and accurate. In combination with simulation paradigms like discrete event simulation and with data bases for stochastically analysing non-energy intensive industries, load profiles for the overall industrial sector can be depicted thoroughly. To wrap these methodologies in a user-friendly way, we embedded the approaches in a standalone application framework to create the software *Ganymed*. This software is executed as an .EXE file and is based upon the Python library Tkinter. All processes within *Ganymed's* GUI can be aligned via drag and drop. They consist of default information e.g. spec. energy consumption, capacity, etc. from literature review, which can be adapted freely by the user. *Ganymed* consists of five key scripts, one of which acts as the main component for connecting all methods in the software framework. Three additionally scripts e.g. methodology for non-energy intensive industries are built in as plugins and are called on user command. The software is free to use and downloadable via *ganymed.ga* [16].

4 LITERATUR

[1] European Environment Agency (2021) Annual European Union Greenhouse Gas Inventory 1990–2019 and Inventory Report 2021

[2] Binderbauer PJ, Staubmann T, Kienberger T (2022) Synthetic load profile generation for production chains in energy intensive industrial subsectors via a bottom-up approach. Journal of Cleaner Production 331:130024. doi:10.1016/j.jclepro.2021.130024

[3] Kebede AA, Kalogiannis T, van Mierlo J, Berecibar M (2022) A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. Renewable and Sustainable Energy Reviews 159:112213. doi:10.1016/j.rser.2022.112213

[4] Dehning P, Blume S, Dér A, Flick D, Herrmann C, Thiede S (2019) Load profile analysis for reducing energy demands of production systems in non-production times. Applied Energy 237:117–130. doi:10.1016/j.apenergy.2019.01.047

[5] Sejkora C, Kühberger L, Radner F, Trattner A, Kienberger T (2020) Exergy as Criteria for Efficient Energy Systems. A Spatially Resolved Comparison of the Current Exergy Consumption, the Current Useful Exergy Demand and Renewable Exergy Potential. Energies 13(4):843. doi:10.3390/en13040843

[6] International Energy Agency (2022) Industry Classification. https://www.iea.org/topics/industry. Zugegriffen: 21. September 2022

[7] Banks J (Hrsg) (2003) Encyclopedia of Information Systems. Discrete Event Simulation. Elsevier

[8] Statistics Austria (2022) Structural Business Statistics 2021

[9] Richard M-A, Fortin H, Poulin A, Leduc M-A, Fournier M (2017) Daily load profiles clustering: a powerful tool for demand side management in medium-sized industries. ACEEE Summer Study on Energy Efficiency in Industry

[10] Industrial Assessment Center (2022) IAC Database

[11] Herold Business Data GmbH (2021) Herold Business Database

[12] Statistics Austria (2022) Useful Energy Analysis 2021

[13] Sen T (2009) Electrical and Production Load Factors. Office of Graduate Studies of Texas A&M University

[14] Binderbauer PJ, Keuschnig A, Kienberger T Synthetic Load Profiles of Non-Energy Intensive Industrial Sites: A Combined Bottom-up and Top-down Approach. (Publication process)

[15] (2022) Graphical User Interfaces with Tk — Python 3.10.5 documentation. https://docs.python.org/3/library/tk.html. Zugegriffen: 12. Juli 2022

[16] (2021) Ganymed Website. Ganymed Software. www.ganymed.ga

5 FURTHER INFORMATION

Ganymed is an .EXE software, executable for Windows® based systems with > 8GB RAM and Intel i5 core or equivalent. Extra licenses or the utilisation of programming languages is not mandatory. *Ganymed* is accessable via *www.ganymed.ga*.

TRANSFORMATION OF SMES IN THE CONTEXT OF THE GREEN DEAL

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Abstract: The EU goal of climate neutrality until 2050 is a considerable challenge for many companies. Especially small and medium-sized enterprises (SMEs) lack the resources to transform their business models towards higher sustainability and climate neutrality. The region of Lower Carinthia is highly affected by the goals of climate neutrality by 2040 in Austria and by 2050 in the EU, due to the high share of carbon intensive industries. For this reason, in the course of the LOCA2-project, the CEOs of 50 companies were interviewed to identify potentials and barriers for the introduction of sustainable business models towards climate neutrality. Furthermore, the interviews allowed to gain an overview on specific processes, used energy carriers, and GHG-emissions of the participating companies. In addition, the Scope 1, Scope 2, and Scope 3-emissions of the different industry sectors in the region in 2019 were analysed. Methodologically a life cycle approach was applied combining statistical input data sources and an environmentally extended input-output-table. Based on these results, transformation paths for selected industry sectors using a dynamic LCA-model were developed. They sketch how the relevant sectors can transform towards climate neutrality. The analysis shows that the transformation is possible, however, the implementation of climate neutral energy carriers has to be accelerated and additional measures such as CCU, CCS, or CDR are necessary to reach net-climate neutrality. A handbook guiding SMEs strategically towards climate neutrality by 2040 is currently being developed.

Keywords: Climate neutrality; transformation pathways; sustainable business models; small and medium-sized enterprises; greening of supply chain; survey; dynamic LCA; EEIO-table.

1 INTRODUCTION

Climate change requires a transformation of the economy towards greenhouse gas-neutral, resource-efficient, and material cycle-oriented activities and business models. However, this aim is difficult to achieve in the existing business logics. The central aim of the LOCA2Transformation (LOwCArbon LOwerCArinthia TRANSformation) project is to enable business executives in the region of Lower Carinthia (districts St.Veit, Wolfsberg, and Völkermarkt) to transform their companies to meet the requirements of the Green Deal, thus to become carbon neutral until 2040/2050. The case of Lower Carinthia can serve as a proxy for many other affected areas worldwide that have to undergo similar transformations. Using an interdisciplinary approach, central potential and barriers of SMEs to move towards climate neutral and circular business models were identified. Furthermore, the energy flows and related emissions of various industry sectors in the region as well as emissions connected to activities in the value chain of companies (Scope 3-emissions) were detected. This data is the empirical basis for the development of so called “transformation pathways” towards climate neutrality. Using 2019 as a starting point, pathways were developed to reduce emissions until 2030 by approximately 61%[1] and to achieve net-zero greenhouse gas- (GHG) emissions in Scope 1 and Scope 2 by 2040 and in Scope 3 by 2050 (EU) and 2060 (rest of the world).[2] The pathways contain information on the technological transformations that have to be realised in order to meet the climate targets.

Energy efficiency and sustainable energy sources are in the centre of these pathways. A meta-perspective was taken to judge on the applicability of new technologies and energy carriers for individual sectors. In addition, the legislative/political requirements for the transformations of business models were considered. Based on a survey, potentials and barriers in the current system were determined and corresponding measures to enable the transformation outlined. As noted before, the concept of sustainable business models (SBMs) was used to sketch, how firms can transform their business activities towards more sustainability. Of great help was the well-known business model canvas of Osterwalder.[1] In order to outline how such a transformation can take place, several examples of companies that successfully adapted parts of their business models towards sustainability were identified in the project.

The transformation towards a climate neutral economy gained more attention in the recent years. In 2019, Geyer et al. [2] discussed the energy consumption of the Austrian industry and deducted transformation pathways based on different scenarios. They delivered an overview over the main technologies and their temporal applicability, based on their technology readiness level (TRL). In 2021, Diendorfer et al. [3] discussed technological pathways for various industry sectors to become climate neutral by 2040 and additionally investigated in “imported” GHG-emissions using an input-output-approach. Baumann et al. [4] focused on possible future supply and demand of renewable gas in Austria in 2021. They found that the production capacities in Austria for renewable gas is limited and that a considerable share of the required H2 for the decarbonisation of the industry will have to be imported. The Austrian Energy Agency [5] analysed the possibilities to substitute Russian natural gas with other energy sources and pointed out that the total energy consumption in Austria should be reduced and they stressed the need for an accelerated implementation of H2 technologies. The installation of an H2 infrastructure for the decarbonisation is also empathised by the Austrian and by the European H2 strategy.[6], [7]

It can be concluded that the decarbonisation of the Austrian industry is a pressing topic and current research shows the need to change the fossil-based system to a circular economy based on renewable energy carriers. However, we identified a research gap concerning specific guidelines for SMEs in the transformation process – especially in the Austrian context. Furthermore, the practical barriers and chances to transform the business models in the Austrian context remained yet widely unknown. This study sheds light on the important issue of practical barriers and studied the particular situation of SMEs in the transformation process. Another new feature is the dynamic LCA-approach used for the development of transformation pathways. The transformation pathway for one sector is illustrated as an example to display the methodology used and to exemplify the outcomes of the study.

[1] a 61% reduction compared to 2019 corresponds to the goal of a 55% reduction as compared to 1990 due to the rise of emissions between 1990 and 2019[3]

[2] For more information on the Scope 1/2/3-framework for GHG-emission reporting, refer to: https://ghgprotocol.org/

2 MATERIALS AND METHODS

2.1 Survey

The study geographically focused on Lower Carinthia, comprising the three districts St.Veit/Glan, Völkermarkt and Wolfsberg. Further, the study comprised industries characterised by high GHG-emissions and/or high pressure for business model transformations towards sustainability. An analysis of high GHG-emissions was carried out to finalise the selection of industries. Following, drawing on the public business register from the chamber of commerce, a total of 158 companies within the selected districts and industries were identified and classified according to the IEA standard.[8] The IEA scheme was applied, to ensure consistency with the LCA part of the study that is based on energy data that was only available in this classification scheme. All 158 companies were contacted personally via phone and received follow-up information with an interview invitation. 50 companies eventually agreed for an interview. As in some industries only a few companies agreed to take part in the survey, the selected IEA categories were merged to guarantee anonymity of participating companies. Finally, 5 groups according to the IEA industry categories were drawn up:

a) *iron and steel; non-ferrous metals; transport equipment; machinery* (27)

b) *wood and wood products; paper, pulp and print; non-specified* (9)

c) *non-metallic minerals* (7)

d) commerce and public *services* (4)

e) *chemical and petrochemical* (3)

Based on recent literature on sustainable business models [9], [10] and particularly on potentials and barriers of their implementation [11], [12], an interview guide containing qualitative and quantitative questions was developed and pre-tested. Qualitative questions followed an investigative-open approach, while quantitative questions were asked using a Likert-scale ranging from 1-6. Secondary data – mainly homepages, sustainability reports and press releases – were screened before the interview and proofed as highly valuable to better understand the context of the companies. Interviews were conducted by two interviewees using the online communication software “zoom”. All interviews, lasting on average one hour, were recorded and transcribed. As for the present paper the quantitative analysis is of no interest, followingly only the qualitative approach will be explained in further detail.

The qualitative part comprised 20 questions. At the beginning, the interviewees were asked to describe their company in general, explaining in further detail their products/services, their customer base, their suppliers, the resources and energy and technologies they mainly use. Following, the focus came to sustainability including digital solutions to conserve resources. The interviewees described measures they already took or were planning to take regarding a circular economy or the prevention of GHG emissions. Further, they were asked what the company needs to be able to change their business model and what they think they have to change within their production process or the products lifecycle. In the end, the interviewees had the chance to add whatever they thought would be of further interest. For the following analysis the qualitative data analysis software MAXQDA was used.[13] In a first step, upper categories were defined. In the concrete case, the suggestions of existing literature to distinguish between company external and internal potential and barriers for sustainable business model transformation was followed. Thereafter, two researchers independently analysed a selection of ten interviews. As the comparison of the created codes and corresponding text passages indicated a strong match of the procedures and assessments of the two researchers, the remaining 40 transcripts were analysed separately. Following the guidelines of Saldana [14] subcategories were streamlined and condensed into fewer ones. For the present paper only the four categories including the internal and external potential and barriers are of interest. The results of these categories will be discussed in the following chapters.

2.2 Carbon Footprint of Industry Sectors

A life cycle assessment (LCA) methodology was applied to determine the GHG-emissions of the industry in Lower Carinthia in 2019, which was the base year of the analysis. To judge on the relevance of the individual industry sectors, a streamlined carbon footprint was calculated for all industry sectors in the area of Lower Carinthia. Sectors with low GHG-emissions, low amount of employees, and low share of SMEs were excluded from further analysis. The same classification scheme as in the survey was applied and all sectors noted in Section 2.1 were analysed in detail.

Based on data retrieved from the database of the Statistik Austria [15], the GHG-emissions of the selected industry sectors were calculated. Therefore, in a first step, the consumption of different energy carriers in the whole Carinthian industry was retrieved from the database and scaled down to the share that was approximately consumed in Lower Carinthia. For the downscaling, the share of persons employed in the target region was used. In a second step, the related Scope 1/2/3-emissions were determined using standard emission factors (mainly derived from GEMIS [16] and from previous research projects). In a third step, data from a so-called environmentally extended input-output-table (EEIO-table) [17] was applied to approximate the emissions related to the up- and downstream activities in the value chains of the different sectors. An important assumption was that the average Austrian value chain was comparable to the average Carinthian value chain of the respective industry sector.

Based on the status-quo analysis the most important sectors were identified and transformation pathways were developed using a so called dynamic LCA approach. In the dynamic LCA a change over time was modeled for the life cycle inventory (in this case the energy consumption) as well as for the emission factors. The time frame for the analysis starts 2019 and ends 2060. An Excel tool was created that was used for scenario modelling. The tool allows to insert parameters on the share of fossil fuels in the electricity grid, energy efficiency, changes in emission factors, economic development of the industry sectors, and the mix of energy carriers/technologies for every single year. Thereby it is possible to determine, what measures have to be introduced in what time frame in order to achieve the political target of net climate neutrality. The introduction of new technologies was mainly based on the before mentioned strategic documents of the Austrian Republic and the European commission, as well as the state-of-the-art reports of Geyer et al. and Diendorfer et al.[2], [3]

3 RESULTS

3.1 Survey Results

The content analysis uncovered many interesting internal & external sustainable business model potential and barriers. A small excerpt is presented in the following:

Internal potential:

1. Many – almost half of the interviewed firms – considered it a large potential to either **install or extend photovoltaic plants** and thus employ green energy in their production processes. Four firms even saw potential for entire **energy self-support**.
2. Besides producing green energy, companies were also aware of the potential to **reduce energy consumption** (6 firms) in their production processes (e.g. by updating machinery, different production processes or deployment of new machinery).
3. A large number (13) of interviewees considered their **product(s) as central in combatting climate change** and thus expect large potential as sensibility on climate change and GHG emissions shall increase.

External potential:

1. Environmentally friendly transportation represented a large challenge for many firms. In this context, for three interview partners it was a large potential that they possessed a **cargo train station**. One interview partner mentioned the large potential for **bundling ordered goods** before they are shipped to companies, especially if they are small and the company is located in a peripheral area.
2. Every fifth interview partner saw potential due to an **increasing demand on sustainable/regional products** and several firms already experienced rising requests in this association.
3. Large external potential was found in the **recyclability of primarily used raw-materials** (11 firms). E.g. steel, one of the primarily component in mechanical engineering can be technically recycled at the end of product life.

Internal barriers:

1. One of five firms was skeptical about the **cost/benefit ratio of sustainability related adjustments & investments** and considered it as an internal barrier. This also included strongly increasing prices for certain components if they were regionally produced.
2. For several firms (5) an internal barrier related to the fact that they did not **own their office and production facilities,** which hindered investments for corresponding sustainability measures (e.g. photovoltaic, insulation).
3. Another internal barrier regarded the **non-recyclability** of certain products (4 firms). In some cases, the products were not repairable at all.
4. Interesting were the insights on **firm size**: while some companies experienced it hindering to be a small company (e.g. fewer financial means), others indicated that a large organization makes it more complicated (less flexibility).
5. Very few firms (2) also mentioned, that they did **not pay (much) attention** to the topic so far, which represented an internal barrier.

External barriers:

1. Almost every third interview partner mentioned **missing political measures** as hindering their business model transformation towards sustainability. These political measures were diverse and related to green energy or regional production (instead or globalisation).
2. For many firms (14), the **lack of climate neutral raw materials** meant a significantt external barrier. As long as the primary raw material is not climate neutral, companies find it difficult to transform their business model towards sustainability.
3. While some interview partners experienced increasing demand on sustainable products (external potential), others (11 firms) complained about a **missing customer**

demand on products with low GHG-footprints. E.g. firms mentioned that not a single customer ever was interested in the GHG reduction of a product.

4 A further external barrier represented a **missing international definition for green electricity**. Discrepancies in this context lead to market distortions, e.g. if nuclear energy is considered as green in one country (and not-green in another country) and hinder sustainable business model transformation.

3.2 Carbon Footprint and Transformation of Selected Industry Sectors in Lower Carinthia

Figure 3-1 shows the GHG-emissions that are related to the energy consumption of the selected industry sectors in Lower Carinthia. It can be seen, that process heat and stationary engines played a major role in the overall GHG footprint in 2019. A significant part of the emissions was related to the use of fossil energy carriers, such as coal, natural gas, waste, and electricity that was partly generated using fossil energy carriers. However, also biomass played a role in the GHG-emissions in 2019, mainly due to the Scope 3-emissions during the harvesting and processing of (fuel-) wood for the pulp and paper industry. We can see that the assumed transformation pathway led to a reduction in the future emissions, however, climate neutrality could not be reached without assuming CCU/CCS/CDR activities.

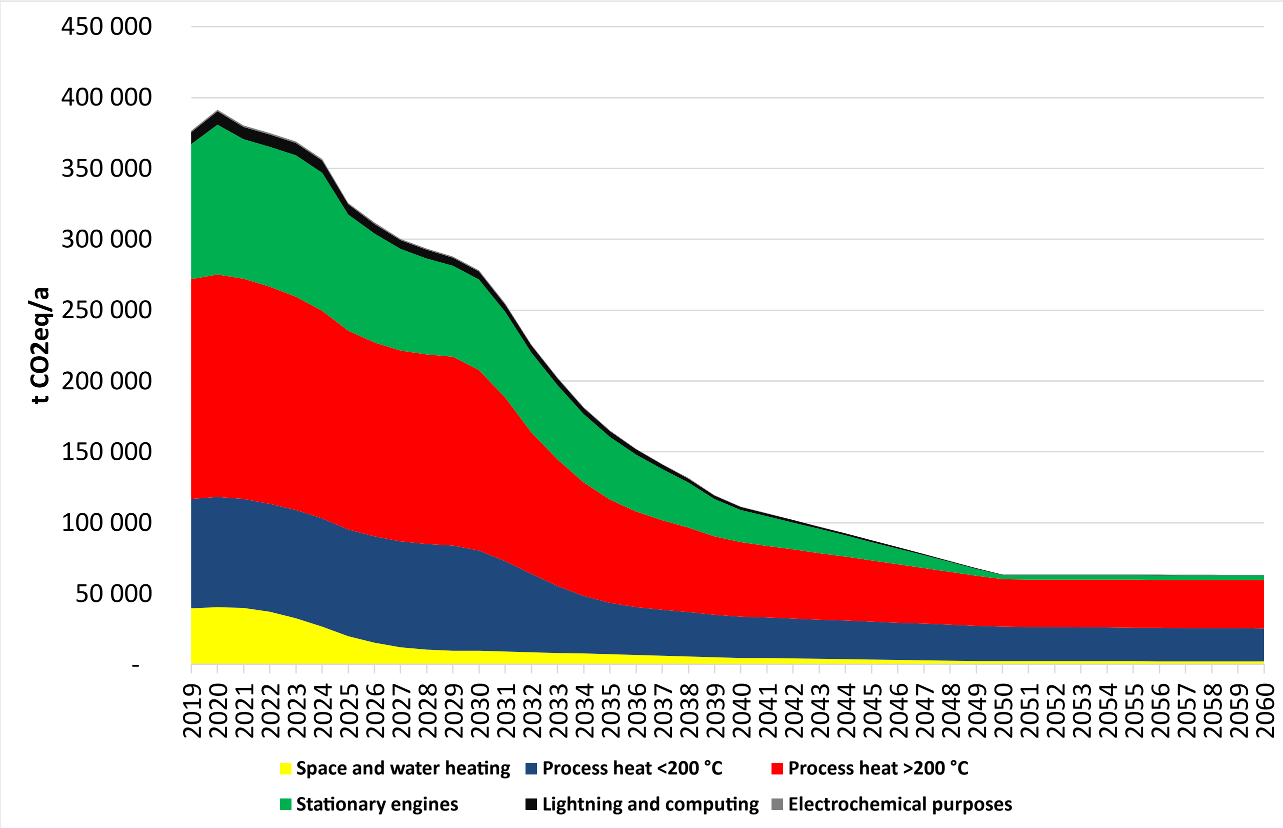

Figure 3-1: Energy related GHG-emissions of selected industry sectors in Lower Carinthia.

Table 3-1 shows the shift in the use of energy carriers that was assumed for the base scenario. Depending on the activity, a change to an alternative energy carrier was modelled in order to reach the goal of climate neutrality. For the base scenario, parameter settings that were judged as consistent with national and international policy goals were used. As can be seen in the diagram, a significant reduction of the energy related GHG-emissions is possible when a shift from fossil fuels to renewable energy carriers is assumed.

Table 3-1: Alternative energy carriers that substitute fossil energy carriers until 2040.

Activity	**Energy carrier 2019**	**Substitute**	**Time of implementation**
Process heat >200 °C	coal	biomass-wood	2022-2031
Stationary engines	gasoline/diesel	biofuel	2022-2031
Space and water heating	heating oil	heat pump COP 3.5	2022-2031
Process heat <200 °C	heating oil	heat pump COP 2.3	2030-2039
Process heat >200 °C	heating oil	wood chips	2022-2031
Space and water heating	LPG/natural gas	heat pump COP 3.5	2022-2031
Process heat <200 °C	LPG/natural gas	heat pump COP 2.3	2030-2039
Process heat >200 °C	LPG /natural gas	67% H2, 33% biomethane	2030-2039
Stationary engines	LPG/natural gas	electricity	2022-2031
Lightning and computing	natural gas	electricity	2022
Space and water heating	waste	heat pump COP 3.5	2022-2031
Process heat <200 °C	waste	heat pump COP 2.3	2030-2039
Process heat >200 °C	waste	50% H2, 50% biomethane; not fully substituted	2030-2034

Figure 3-2 shows the emissions of the sector machinery from 2019 to 2060. In addition to Figure 3-1, not only the energy related Scope 3-emissions are indicated, but also the emissions related to other activities in the value chain, such as raw material procurement and transports.

Table 3-2 indicates that the Austrian goal to achieve a GHG-emission reduction of 61% (based on the goal of 55% reduction compared to 1990) between 2019 and 2030 cannot be reached using the parameters of the base scenario. At the aggregated level of all selected industry sectors, the goal of net carbon neutrality of Scope 1 and Scope 2-emissions until 2040 was not reached in the model. This was mainly due to the high emissions related to process energy.

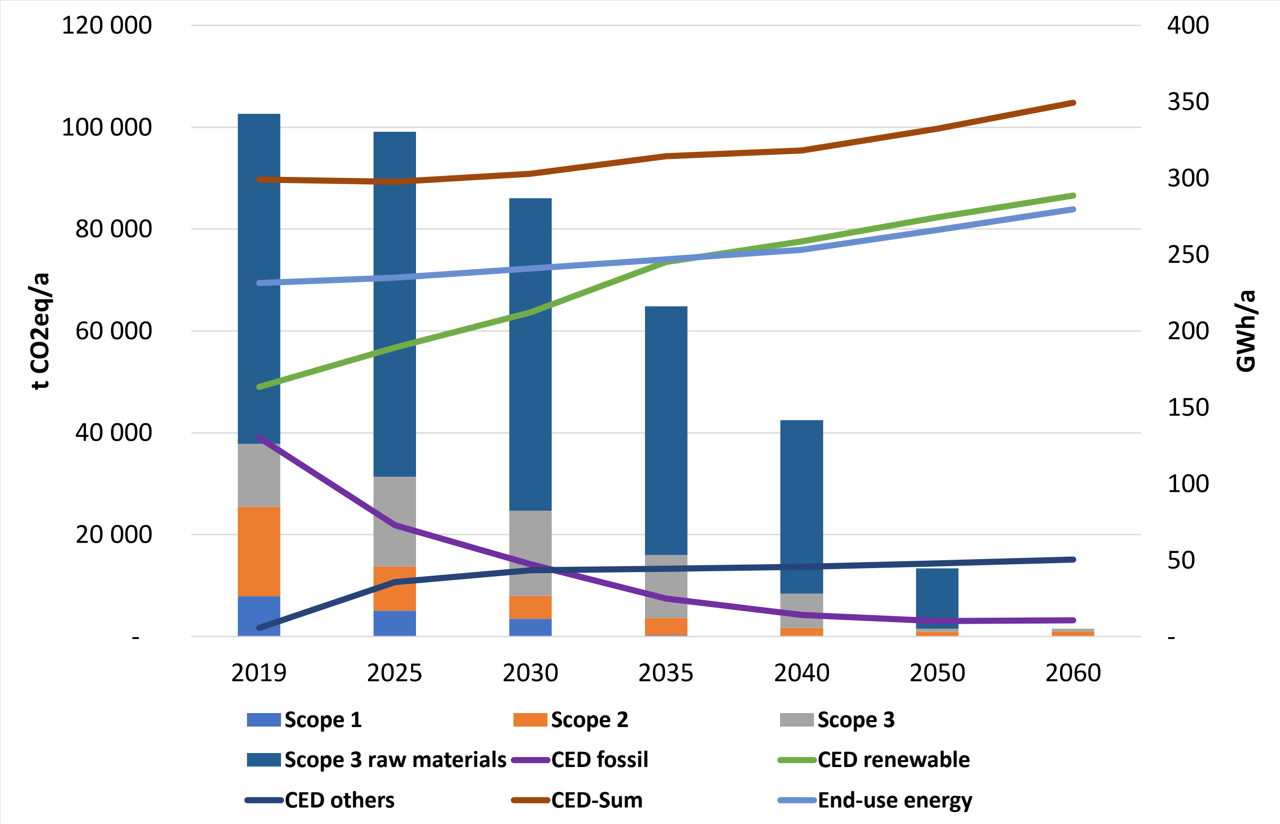

Figure 3-2: Energy related Scope 1/2/3-emissions of the sector machinery including Scope 3-emissions for up and downstream value chain "raw materials", cumulative energy demand, and consumed end-use energy.

Table 3-2: GHG-Emissions reduction of selected industry sectors/machinery as compared to the base year 2019 and required CCU/CCS/CDR to meet the climate goals.

Year	**Total Selected Industries: Reduction of Scope 1 and 2-Emissions compared to 2019 [%]**	**Machinery: Reduction of Scope 1 and 2-Emissions compared to 2019 [%]**	**Reduction plan Austria [%]**	**CCU/ CCS/CDR for all selected industry sectors [t CO2eq]**
2025	29	46		0
2030	46	69	61	38 358
2035	82	86		0
2040	88	93	100	30 870
2050	89	96		27 361
2060	89	96		28 760

The table furthermore shows that there is a demand for CCU/CCS/CDR to meet the climate goals. On the one hand, due to the late implementation of renewable energy systems and on the other hand, for the compensation of the remaining GHG-emissions, that are costly or hard to reduce. It can be seen that for this particular industry sector the non-energy related Scope 3-emissions (mainly the production of raw materials) were higher than the energy related Scope 1/2/3-emissions in 2019. Hence, it can be concluded that there is a strong need for an emission reduction in the up- and downstream value chain of the sector machinery, so that it can meet the goal of overall climate neutrality. In addition, the cumulative energy demand

(CED) is indicated in the graphic, showing a significant increase in renewable energy consumption, stressing the need for an expansion of renewable energy carriers.

Table 3-3 shows the share of different activities in the total non-energy Scope 3-activities of the sector machinery. It can clearly be seen, that a major share of the Scope 3-emissions is related to the use of fabricated metal products, basic iron and steel, aluminium and electrical equipment. Hence, an emission reduction in the whole value chain of the sector machinery requires a significant transformation of the metal producing industry that supplies the machinery sector.

Table 3-3: Share of different activities (mainly raw material production) in the non-energy related Scope 3-emissions of the industry sector "machinery".

Industry Sector	Share in Scope 3-emissions [%]
Fabricated metal products	17
Basic iron and steel and ferro-alloys	14
Electrical machinery	8
Aluminium	8
Machinery	7
Wholesale trade	7
Other business services	5
Rest	29

Another aspect of the project was to identify the amount of renewable energy needed in the future. The model shows that an increase of more than 42% of the current amount of electricity is needed to serve the future electricity and H2 consumption as assumed in the base scenario. Biogen energy carriers (mainly from wood) show an increase of 16%.

4 DISCUSSION AND CONCLUSION

The results of the survey showed many different barriers and potentials for the transformation of business models. Some even contradicted each other as it was the case for the firm size. It was found that the potential of reducing the energy amount used and of producing at least some of the energy used autonomously was rather high. In addition, there is a significant potential regarding transportation. Barriers comprised a lack of knowledge and financial means on the one hand and missing political measures and a lacking availability of climate neutral raw materials on the other hand. Different recommendations for future actions of diverse actors can be derived from the results. These recommendations will be of interest for both policy makers and the funding body. Policy makers shall offer informative material on the requirements of the Greed Deal for companies. Further, individual consultation on potential changes and on the variety of funding options may be favourable for the transformation. Funding bodies may be well advised to offer training for and/or promote the introduction of an energy expert within the companies. Especially the certification of such an expert may be an incentive for employees to take part in a training. In addition, also the introduction of a pool of experts that can be contacted from each company, if required, may be helpful. This may also increase the distribution of knowledge between different companies.

The GHG emission-model shows how a possible transformation can look like for the carbon-intense industry sectors in Lower Carinthia. Based on realistic assumptions, a base scenario was modelled to clarify whether the political goals of climate neutrality can be reached. The results indicate that for the entire region it is hardly possible to reach the climate goals in the given time frame without additional measures (such as CCU/CCS/CDR) or a drastic reduction of the emission factors of renewable energy sources. Further measures, such as highest possible reduction of GHG-emissions of renewable energy carriers, extensive efficiency gains, and possibly also a rethinking of the type of products that are manufactured should be considered. However, for single industry sectors like the sector machinery, the goal of 61% reduction in Scope 1 and Scope 2 by 2030 seems reachable supposing the assumptions of the base scenario. The results urge the need for the further development of renewable electricity and biomass to meet the future industry demand. The model furthermore shows the highest contributors to the non-energy related Scope 3-emissions of the individual sectors. Based on these results, measures in the upstream- and downstream value chain can be derived, e.g. the necessary supply of green steel in order to reduce the Scope 3-emissions of the machinery sector.

The low – but still significant – level of GHG-emissions after 2040 indicates a strong need for CCU/CCS/CDR technologies. However, these technologies yet face several limitations. Depending on the industry sector, different approaches can be applied. In the case of high concentrated GHG-emissions, as in the sectors “pulp, paper, and print” and “non-metallic minerals”, the direct capture from exhaust gases using amine gas treatment could be an option. The sequestrated CO_2 could be used for the production of synthetic fuels or polymers or stored in geological formations.[18], [19] Remaining emissions could also be offset by the extension of biological sinks (e.g. through reforestation). However, the availability of technical and biological CO_2-sinks seems to be limited, hence, the avoidance of GHG-emissions should be preferred where possible.[20]

This study has a number of limitations. It can be assumed that especially companies that were already interested in the topic or even already took steps to a more sustainable business model agreed to an interview (self-selection bias). Therefore, results may only reflect barriers and potentials for these firms. Furthermore, knowing from the ex-ante phone call, interview partners knew that the interview was about sustainability and therefore presented themselves from a sustainable viewpoint (social desirability bias). Also concerning the carbon footprint of the industry sectors, several limitations can be named. One is the lacking of detailed data on energy consumption in the region of Lower Carinthia, which made it necessary to approximate the consumption as described above. Furthermore, the choice of emission factors (especially for renewable energy carriers) can have a significant influence on the overall results. Another limitation is that the used EEIO-table represents a very rough estimation on the related average Scope 3-emissions of Austrian industry sectors and therefore the applicability in the specific region of Lower Carinthia is very limited. In addition, for this paper the process emissions of the non-metallic minerals sector were not considered.

The study was a first approach to develop a framework for the decarbonisation of a region with a high share of GHG-intense industries. We were able to identify potentials and barriers to a transformation towards climate neutrality and we outlined possible transformation pathways. Our study design proved as useful to sketch the necessary technological developments in the transformation. However, due to the limitations of our methodological framework, we recommend to focus on the generation of more reliable data on energy consumption and Scope 3-emissions for future studies.

For future research it may be of interest to further analyse which specific changes are most difficult due to a lack of financial means. Thus, a more purposeful funding could be offered. Learnings from the LOCA2 project are transferable to other regions easily, especially in the Austrian context, as a broad variety of industry sectors was analysed on a macro-level. The handbook can serve as a guideline towards climate neutrality for the different industry sectors and will be available by the end of 2022. We hope that decision makers will use it as a blue print for the transformation towards climate neutrality and circular economy.

5 FUNDING

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6 REFERENCES

[1] A. Osterwalder and Y. Pigneur, *Business Model Generation: Ein Handbuch für Visionäre, Spielveränderer und Herausforderer*. Campus Verlag, 2011.

[2] R. Geyer, S. Knöttner, C. Diendorfer, and G. Drexler-Schmid, ‘Energieinfrastruktur für 100 % Erneuerbare Energie in der Industrie’, 2019.

[3] C. Diendorfer *et al.*, ‘Klimaneutralität Österreichs bis 2040. Beitrag der österreichischen Industrie’, 2021.

[4] Martin Baumann, Karin Fazeni-Fraisl, Thomas Kienberger, and Peter Nagovnak, ‘Erneuerbares Gas in Österreich 2040. Quantitative Abschätzung von Nachfrage und Angebot Endbericht’, 2021. Accessed: Jul. 13, 2022. [Online]. Available: https://www.bmk.gv.at/dam/jcr:2486be49-85cd-41d6-b2af-a6538757e5cd/Erneuerbares-Gas-2040.pdf

[5] ‘Strategische Handlungsoptionen für eine österreichische Gasversorgung ohne Importe aus Russland’, Wien, 2022. [Online]. Available: www.energyagency.at

[6] Bundesministerium für Klimaschutz, ‘Wasserstoffstrategie für Österreich’, Wien, 2022.

[7] ‘Eine Wasserstoffstrategie für ein klimaneutrales Europa’, Brüssel, 2020. [Online]. Available: https://www.eu2018.at/de/calendar-events/political-

[8] Statistik Austria, ‘Standard-Dokumentation. Metainformationen (Definitionen, Erläuterungen, Methoden, Qualität) zur Nutzenergieanalyse’, Wien, 2013. [Online]. Available: www.statistik.at

[9] N. Sinkovics, D. Gunaratne, R. R. Sinkovics, and F.-J. Molina-Castillo, ‘Sustainable Business Model Innovation: An Umbrella Review’, *Sustainability*, vol. 13, no. 13, p. 7266, Jun. 2021, doi: 10.3390/su13137266.

[10] L. C. Comin, C. C. Aguiar, S. Sehnem, M.-Y. Yusliza, C. F. Cazella, and D. J. Julkovski, ‘Sustainable business models: a literature review’, *Benchmarking: An International Journal*, 2019.

[11] V. Rizos *et al.*, ‘Implementation of Circular Economy Business Models by Small and Medium-Sized Enterprises (SMEs): Barriers and Enablers’, *Sustainability*, vol. 8, no. 11, p. 1212, Nov. 2016, doi: 10.3390/su8111212.

[12] D. A. Vermunt, S. O. Negro, P. A. Verweij, D. V. Kuppens, and M. P. Hekkert, ‘Exploring barriers to implementing different circular business models’, *J Clean Prod*, vol. 222, pp. 891–902, Jun. 2019, doi: 10.1016/j.jclepro.2019.03.052.

[13] H.-F. Hsieh and S. E. Shannon, ‘Three Approaches to Qualitative Content Analysis’, *Qual Health Res*, vol. 15, no. 9, pp. 1277–1288, Nov. 2005, doi: 10.1177/1049732305276687.

[14] J. Saldana, *The coding manual for qualitative research*, 2nd ed. London: Sage Publications, 2013.

[15] Statistik Austria, ‘Nutzenergieanalyse’. STATISTIK AUSTRIA, 2022.

[16] ‘GEMIS 4.9.3’. https://www.umweltbundesamt.at/angebot/leistungen/angebot-cfp/gemis (accessed Jul. 13, 2022).

[17] ‘Exiobase 3.3.18’.

[18] R. Friedle, C. Dankl, J. Juhart, K. Bergmeister, and M. Menge, ‘5. Grazer Betonkolloquium’, 2022.

[19] S. Spaun, C. Bauer, C. Dankl, R. Friedle, and F. Papsch, ‘Wie Was Wann - Roadmap zur CO2-Neutralität der österreichischen Zementindustrie bis 2050’, Wien, 2022.

[20] G. Luderer, C. Kost, and D. Sörgel, Eds., *Deutschland auf dem Weg zur Klimaneutralität 2045*. Potsdam, 2021. doi: 10.48485/pik.2021.006.

ENERGY OPTIMIZATION OF A BAKERY

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** **Winner of the Young Scientist Award**

Abstract: The development of tools that provide effective energy efficiency measures are crucial in order to achieve CO_2 reduction targets. Bread is among the most energy intensive food products, which is due to the thermal processes involved in their manufacturing [1]. To date bakeries are less energy efficient compared to large baked goods factories [2]. The present work presents a data-supported analysis of the current state of the baked goods production of a medium-sized bakery in Graz. The potential for energy efficiency and load balancing in the form of optimized baking job scheduling is identified. Consequently, the scheduling problem is tackled using a two-stage approach focusing on reducing total energy consumption and peak load. The resulting baking schedule includes the assignment of baked goods to ovens and considers the load of the remaining production units as a background load profile.

Keywords: job scheduling, energy efficiency, load balancing, baked goods production

1 INTRODUCTION

In Austria, the industry sector is responsible for about 1/3 of total final energy consumption [3] and for 44% of CO_2 emissions [4]. Energy efficiency and reduction in CO_2 emissions are therefore crucial in order to achieve the CO_2 reduction targets of the Paris agreement/COP21. In this light, the research and application of approaches like demand-side management (DSM), that can pave the way for integration of renewable energy for industrial systems, is of utmost importance [5] [6]. DSM refers to a series of techniques and measures aimed at modifying the demand side energy consumption pattern to foster better efficiency and operations in energy systems [7]. Generally DSM activities can be grouped into the categories energy efficiency (EE) and demand response (DR) [7] [8]. DSM aids to provide the flexibility needed to handle volatile energy sources and at the same time reduces the strains on the energy infrastructure (e.g. electricity grid) by optimal scheduling in industrial plants. As an additional advantage, the total energy consumption as well as the required storage capacities can be reduced. The Austrian research project DSM_OPT aims to develop a DSM decision support system toolbox for optimal industrial process scheduling. The project is part of the NEFI (New Energy For Industry) model region, that positions energy intensive and manufacturing industries and their decarbonisation in the centre of a long-term innovation process to boost technological development.

Within the project DSM_OPT two case studies are investigated, one of which specifically investigates the production of baked goods at a bakery. Within the Austrian industrial sector, food production accounts for 8 % of energy consumption [9] and more than 3 % of the emissions of climate-damaging greenhouse gases [4]. Bread along with instant coffee, milk powder, French fries, and crisps are among the most energy intensive food products, which is due to the thermal processes involved in their manufacturing, that consume large proportions of the total processing energy [1]. The high energy intensity of baking processes is related to the low values of convective heat transfer coefficients through air (approx. 30 W/m2K) [10]. However, both the energy consumption (MJ/kg baked goods) as well as the greenhouse effect (g CO_2-equiv./kg baked goods) of small bakeries are estimated to be twice as high compared to large bread factories [2]. Hence, the need for energy efficiency measures targeting not only large but also small bakeries especially focusing on the baking process is apparent. The authors of [11] suggest to minimize oven operating time and reduce standing losses by implementing optimized baking scheduling. Likewise, [12] list the scheduling of baking processes as a good practice opportunity that involves low implementation cost and is applicable at 90% of the production sites. They expect the CO_2 saving potential to be significant, but clarify that further research is required for quantification.

There have been efforts to tackle the scheduling problem in bakeries in the past by research groups from different fields, most of which focus on economic objectives and production time. In [13] a bakery production supplied by electric energy solely was analysed using different key performance indicators (e.g. peak demand, respective time during production week and energy consumption per process). Consequently a genetic algorithm was employed for job scheduling optimization minimizing the electricity cost and the makespan. In [14] a particle swarm optimization and an ant colony optimization were used to achieve optimal scheduling of the production process in a bakery focusing on minimizing the makespan and the total idle time of the machines. The authors of [15] modelled the scheduling problem as a mixed integer linear programming problem and maximized for profit.

The present work focuses on energy efficiency and load balancing for the production of a local bakery. In a first step the production is analysed to identify the potential of operation related energy efficiency measures. Consequently a methodology tailored to achieve optimal scheduling of baking processes is developed. Hereby the aforementioned suggestions regarding baking scheduling made in [11] and [12] are addressed by optimizing for energy efficiency as well as for a balanced load profile. In this regard energy consumption and peak load are chosen over the economic cost functions, which were commonly used in the past, to focus on sustainability. Similarly to the approach taken in [15] one part of the optimization problem is tackled using integer linear programming, while the second part is optimized using a non-linear optimization approach.

2 MATERIALS AND METHODS

2.1 Analysis of the production process

Initially pre-existing data was collected and processed in order to clean individual data sets and organize them. Consequently the existing data base was surveyed to identify gaps in the current data acquisition system of the bakery. On this basis a plan for the implementation of additional measuring equipment at strategically important sites was developed to guarantee a sufficiently large and detailed data base for further research activities. The available data was processed further and analysed using descriptive statistics as well as data visualization.
Concurrently a qualitative analysis of the production process was carried out involving on-site inspections as well as close cooperation and discussion between the research team and the technical staff of the bakery. The methods used, included estimation of the energy

consumption of different sub-processes, generation of flow diagrams of the production processes, identification of bottlenecks and potentials for energy efficiency measures and were based on measured data from the past as well as bakery specific expertise and the experience of the experts involved.

2.2 Optimization of production planning

For optimization the findings of the preceding analysis were used to identify the potential for flexibility in the production process and determine possible variables for optimization. For the optimization itself two python libraries were used: On the one hand PuLP [16], a Python-based optimization tool that provides a framework for linear and mixed integer programming, was used for partitioning type problems. These are relevant for optimally distributing baking jobs among the ovens available. On the other hand the SciPy [17] implementation of the Nelder-Mead method was used. This method provides the possibility to optimize nonlinear functions without requiring derivatives. While it shows linear convergence properties only, this method can be considered robust - a highly desirable property for practical applications. For this application an iterative process calling the optimizer using randomized initial conditions and a randomized initial simplex was implemented. Finally the best optimization result is returned.

3 RESULTS

3.1 Analysis of the production process

The production process at the bakery is affected by many factors some of which are seasonal like ambient temperature, school holidays and seasonal products, but there are also fluctuations on a smaller time scale like special products and different production volume for various holidays or non-scheduled orders for events. Additionally, the purchase behaviour of the average consumer seems to be partly dependent on weather conditions. The production planning is based on long-standing experience and is performed using a twofold strategy: On the one hand there is long term planning involving a large product volume for corporate clients. On the other hand there is short term planning needed for the supply of the bakery shops, which takes place in form of a baking list that is issued every day for the production of the subsequent day. Hence, the ovens and other machines involved in dough preparation are operated in a highly variable fashion, but there is flexibility with regard to their operating times within the period of one production day. The cooling system however permits minimal flexibility, since it is mainly used for storage, interruption of fermentation or interim storage and therefore run non-stop at constant temperature levels.

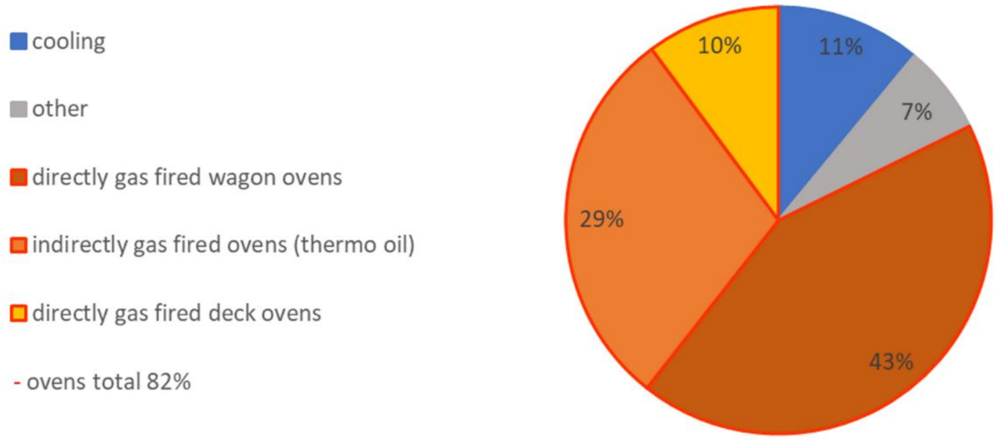

Figure 3-1: Total energy usage in the bakery mapped to the different consumers

Looking at how the energy consumption is distributed over the different processes in the production, see Figure 3-1, it is apparent that baking is the most energy intensive process in the bakery followed by cooling. This finding is consistent with the literature. In [12] the authors state, that in the baked goods production most energy is used in baking and cooling and that baking accounts for 45% of CO_2 emissions. In [11] baking is stated to account for 26%-78% of the product-specific energy consumption for production.

It is insightful to zoom in on the baking process and look at the oven operating modes (standby, heating up, baking) and the time and energy spent when each of these modes were active, see Figure 3-2. 42% of the total operating time of the gas fired wagon ovens is spent in standby mode, which translates to 17% of the energy, which is a potential for energy efficiency optimization. For the present case the implementation of an optimized baking schedule seems to be feasible in combination with appropriate intermediate storage variants like long term guttering up to two weeks for semi-baked products in order to enable further temporal flexibility in the baking process and reduce frequent freezing and defrosting processes.

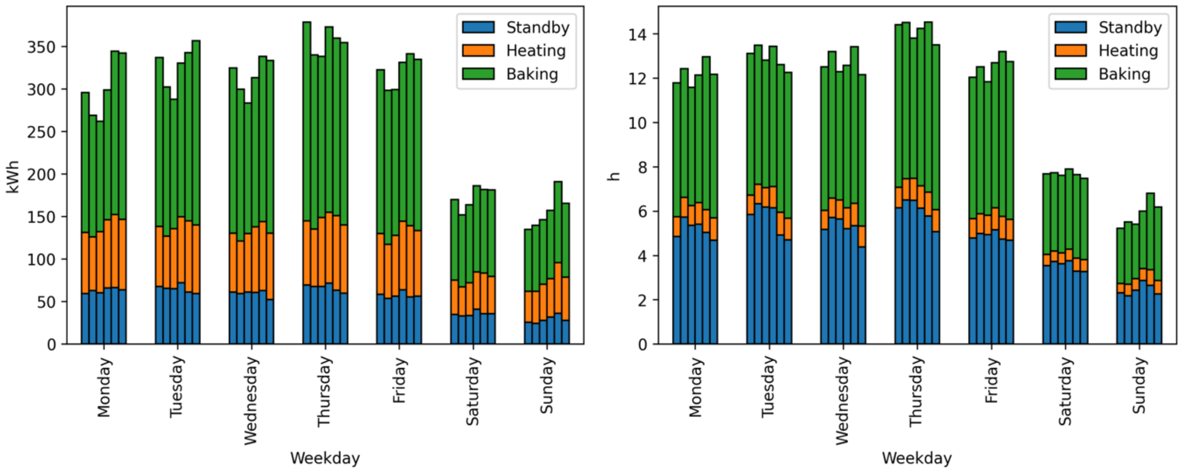

Figure 3-2: Energy (left) and time (right) used by the directly gas fired wagon ovens in standby mode, for heating up and baking. The data depicted in this graphic was collected over 6 months in 2021.

3.2 Optimization of production planning

Based on the findings of the preceding analysis, the production planning optimisation focuses on scheduling the time of use of the ovens. The scheduling problem is tackled using a two-stage procedure:

1. Distributing the baking jobs among the ovens and determining the optimal baking sequence for each oven.
2. Determining the optimal time for each oven to run under consideration of a background load (remaining energy demands).

As a starting point for the design of the two-stage optimization routine, the real oven load profiles as well as the background profiles were replaced by surrogate profiles. This enabled the development of a robust optimisation procedure at the current stage of research. In later stages of the project, these oven load surrogate profiles will be replaced by real product specific load profiles measured during production. The background profile is expected to exhibit periodic behaviour over the course of one day and may therefore be modelled from measured data and extended by adding expected special events or environmental influences like ambient temperature using forecasting methodologies.

Stage 1:

The problem in stage one can be formulated as a partitioning problem and solved using linear optimization techniques provided by PuLP [16]. The objective function E_{tot} reads:

$$E_{tot}(x_{ij}) = \sum_{j}^{N} \sum_{i}^{n} x_{ij} \, E(o_{j,} p_i) \tag{3-1}$$

Here, $E(o_{j,}p_i)$ is the total energy consumed by oven j considering the baking job sequence i. N is the total number of ovens and n is the total number of possible baking job sequences. The integer valued coefficients x_{ij} are chosen such that the total energy consumed E_{tot} is minimized. In order to guarantee that every oven and every baking job is unique and the baking time available per oven is finite, appropriate constraints are added. For the calculation of the $E(o_{j,}p_i)$ the surrogate load profiles of the baking jobs are summed up to one single load profile per oven according to the respective sequence. In this calculation the energy and time needed for heating up in case the change in baking temperature is positive is considered. In case a baking job is followed by another using a lower temperature, no energy and time for heating up is added. Consequently $E(o_{j,}p_i)$ is calculated from the resulting oven load profile.

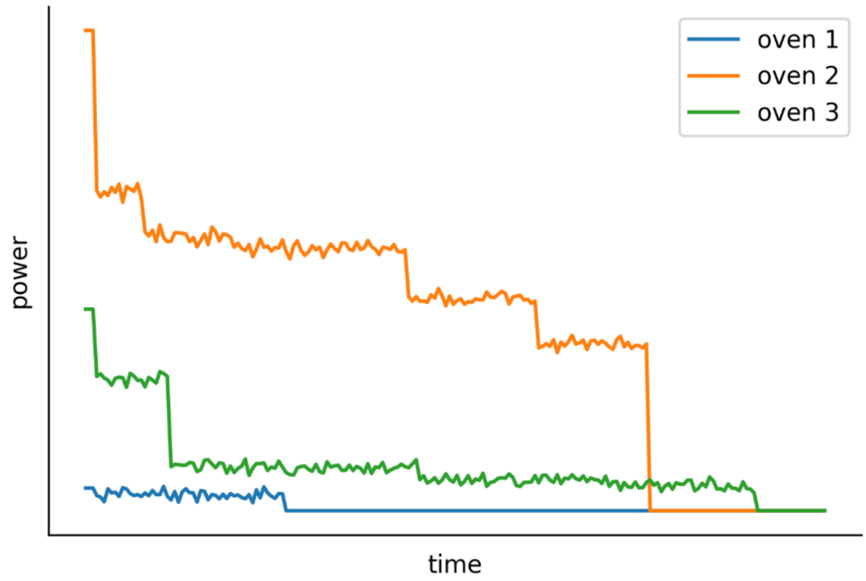

Figure 3-3: Optimized partitioning of the surrogate single product load profiles

In Figure 3-3 the partitioning and sequencing of an optimization run considering 12 different baking jobs and 4 available ovens is shown. From the plot three important characteristics shown by the optimization procedure are evident:

1. The finite baking time available enforces a distribution of the baking jobs among multiple ovens. However the lowest number of ovens possible is chosen, thus only 3 out of 4 ovens are scheduled to be operated.
2. The baking jobs are distributed among ovens building groups of similar temperature, which contributes to keep the energy used for heating up at the start of the sequence minimal.
3. Baking jobs are ordered from high temperatures (which correlates to a high power consumption) to low temperatures in order to avoid heating up in between baking jobs and hence minimizing energy consumption.

Note that in practice the reverse order (from lower to higher temperatures) is a similarly good option and might be a likewise optimal solution depending on the process of heating up. Baking job sequences mixing temperature levels however a clearly not optimal since the amount of energy used for heating up in between baking jobs is not minimal.

Stage 2:

The second stage of optimization aims to find the optimal times for each oven to start to execute the baking job sequences assigned to them in step 1 considering a background load profile. This background load profile may consist of contributions like energy consumption originating from cooling, room heating or compressed air production. For the optimization process the total load p_{tot} is calculated by adding the background load profile p_{bg} to the sum of all N time shifted single oven load profiles p_j.

$$p_{tot}(t, \boldsymbol{t_{start}}) = p_{bg}(t) + \sum_{j}^{N} p_j(t + t_{start}^{j}) \tag{3-2}$$

Note, that here $\boldsymbol{t_{start}}$ is a vector consisting of all oven start times t_{start}^{j}. In order to choose $\boldsymbol{t_{start}}$ in an optimal fashion, different objective functions $C(\boldsymbol{t_{start}})$ were investigated. On the one hand a squared variation of the load profile was considered to penalize large fluctuations in the load profile:

$$C_1(\boldsymbol{t_{start}}) = (p_{tot}(t_{i+1}, \boldsymbol{t_{start}}) - p_{tot}(t_i, \boldsymbol{t_{start}}))^2 \tag{3-3}$$

where t_i and t_{i+1} are consequent time steps. On the other hand the maximum:

$$C_2(\boldsymbol{t_{start}}) = \max_i p_{tot}(t_i, \boldsymbol{t_{start}}) \tag{3-4}$$

was utilized to put a special focus on reducing the peak load. The following linear combination of Equation (3-3) and (3-4) yielded the best results:

$$C(\boldsymbol{t_{start}}) = \alpha(p_{tot}(t_{i+1}, \boldsymbol{t_{start}}) - p_{tot}(t_i, \boldsymbol{t_{start}}))^2 + \beta \max_i p_{tot}(t_i, \boldsymbol{t_{start}}) \tag{3-5}$$

Here α and β are weighting factors, which were chosen to be $\alpha = \frac{1}{2}\beta$ for the optimization of the results shown in Figure 3-4. The optimization itself was implemented using the SciPy [17] implementation of the Nelder-Mead as discussed in section 2.2.

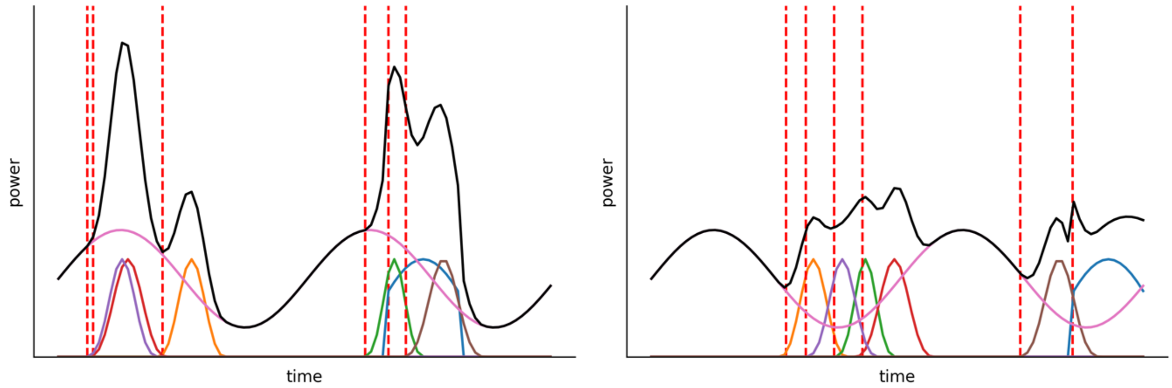

Figure 3-4: Starting times (dashed red lines) of six surrogate single oven load profiles (coloured) considering a surrogate background load profile (brown) and the total load (black) before (left) and after (right) optimization

In Figure 3-4 on the left the initial state for optimization with randomly chosen $\boldsymbol{t_{start}}$ is shown. The total load exhibits significant peaks due to disadvantageous timing of the single oven load profiles. The right plot shows the timings after optimization. In this example the maximum load, eq. (3-1), was reduced by 46% and the squared variation of the curve, eq. (3-3), was reduced by 86%.

4 DISCUSSION

In the present work energy efficiency and load balancing for the production of a bakery was addressed. Initially the production system was assessed and analysed. The ovens were identified as the main energy consumers, followed by the cooling system. The best opportunity for flexibility concerning those main energy consumers was found to be the timing of the baking jobs within the timespan of one day to guarantee timely production for punctual delivery of the products to the bakery shops and other customers. In this respect employing a baking schedule at the bakery is recommended to reduce energy consumption caused by ovens in standby mode on the one hand and to minimize energy used for heating up ovens in between baking jobs on the other hand.

For this purpose a two-stage baking job scheduling optimization procedure was developed, that takes a production list along with the respective load profiles for each baking job as an input and produces a baking schedule including the assignment to the ovens and timings needed for production. The optimal baking schedule takes a background load as well as the energy and time needed to heat up between different baking jobs into account and focuses on load balancing and energy efficiency.

In contrast to past works developing optimal scheduling for the production of baked goods, which mainly focus on economic considerations for optimization [13] [14] [15], the present approach focuses on energy efficiency and load balancing. To promote a better acceptance of the tool however, an incorporation of economic parameters as a result of the above described measures is obvious and planned as a next step. While some works take the whole production line into account [13] [14] [15] the former two of which do so with a lower degree of detail, the present work focuses on the most energy intensive process only and optimizes it in a detailed fashion.

It is important to note, that at the present moment the optimization process operates using surrogate load profiles only. To reach the end goal of developing a decision-support system for maximal energy efficiency and minimised energy demand, realistic load profiles modelled from measurements to replace the surrogate profiles and finally validation experiments in the bakery are necessary. For this reason a plan for the implementation of additional measuring equipment at strategically important sites was developed to enable further research activities regarding the job scheduling module as a part of the DSM_OPT toolbox. Finally the tool will be incorporated by the bakery to aid the production manager in planning baked goods production in an energy efficient manner and avoiding load peaks by recommending an optimal baking job schedule based on the daily production list.

Future research interests include the integration of volatile renewable energy sources. The basic functionality of the optimal scheduling process provides the opportunity to shift loads in the production process. This functionality can be utilized to schedule baking in order to optimally consume the currently available renewable energy by incorporating respective time slots and/or energy supply profiles in the objective function used for optimization.

5 REFERENCES

[1] A. Ladha-Sabur, S. Bakalis, P. J. Fryer and E. Lopez-Quiroga, “Mapping energy consumption in food manufacturing,” *Trends in Food Science & Technology,* 2019.

[2] J. Braschkat, A. Patyk, M. Quirin and G. Reinhardt, “Life cycle assessment of bread production-a comparison of eight different scenarios,” *DIAS report,* 2004.

[3] STATISTIK AUSTRIA, “Energiebilanzen,” [Online]. Available: https://www.statistik.at/statistiken/energie-und-umwelt/energie/energiebilanzen. [Accessed 2022].

[4] STATISTIK AUSTRIA, “STATcube - NAMEA ab 1995,” [Online]. Available: https://statcube.at/. [Accessed 2022].

[5] F. Boshell and O. Veloza, “Review of developed demand side management programs including different concepts and their results,” in *2008 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America*, 2008.

[6] A. F. Meyabadi and M. H. Deihimi, “A review of demand-side management: Reconsidering theoretical framework,” *Renewable and Sustainable Energy Reviews,* 01 12 2017.

[7] M. Behrangrad, “A review of demand side management business models in the electricity market,” *Renewable and Sustainable Energy Reviews,* 2015.

[8] I. Lampropoulos, J. K. W. van den Berg and P. F. Ribeiro, “History of demand side management and classification of demand response control schemes,” in *Proceedings of the IEEE Power and Energy Society General Meeting*, 2013.

[9] STATISTIK AUSTRIA, “STATcube - Energiegesamtrechnung ab 2008,” [Online]. Available: https://statcube.at/. [Accessed 2022].

[10] J. Klemes, R. Smith and J.-K. Kim, Handbook of water and energy management in food processing, Cambridge, UK: Woodhead Publishing Limited, 2008.

[11] P. Therkelsen, E. Masanet and E. Worrell, “Energy efficiency opportunities in the U.S. commercial baking industry,” *Journal of Food Engineering,* 2014.

[12] C. Trust, “ Industrial Energy Efficiency Accelerator Guide to the industrial bakery sector”.

[13] Y. Wang, K. Li, S. Gan and C. Cameron, “Analysis of energy saving potentials in intelligent manufacturing: A case study of bakery plants,” *Energy,* 2019.

[14] F. T. Hecker, W. B. Hussein, O. Paquet-Durand, M. A. Hussein and T. Becker, “A case study on using evolutionary algorithms to optimize bakery production planning,” *Expert Systems with Applications,* 2013.

[15] F. A. M. da Silva, A. C. Moretti and A. T. de Azevedo, “A Scheduling Problem in the Baking Industry,” *Journal of Applied Mathematics,* 2014.

[16] J.-S. Roy and S. A. Mitchell, “https://github.com/coin-or/pulp,” [Online]. [Accessed 2022].

[17] P. Virtanen, R. Gommers, T. E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright, S. J. van der Walt, M. Brett, J. Wilson, J. Millman, N. Mayorov, A. Nelson, E. Jones, R. Kern, E. Larson, C. J. Carey, I. Polat, Y. Feng, E. Moore, J. VanderPlas, D. Laxalde, J. Perkold, R. Cimran, I. Henriksen, E. A. Quintero, C. Harris, A. Archibald, A. Riberio, F. Pedregosa, P. van Mulbregt and SciPy 1.0 Contributors, “SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python,” *Nature Methods,* 2020.

[18] M. Lauermann, “https://www.nefi.at/eddy/,” 2022. [Online]. Available: https://www.nefi.at/eddy/.

V. Presentations: New industrial Processes - Industrial Heat Utilisation

EJECTOR TECHNOLOGIES FOR PERFORMANCE INCREASE OF INDUSTRIAL HEAT PUMPS

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Abstract: Industrial energy systems need to be decarbonized substantially. High temperature heat pumps show large potential in supplying sustainable heat for energy intensive process industries. However, the technology comes with limited performance when high temperature lifts are required. In a national feasibility study, ejectors proved a viable device for partially recovering expansion work lost. For two industrial heating applications, one for steam production at supply temperatures of 130°C and one for industrial drying at 160°C, average increases in heating capacity of 10% resp. 9% and efficiency increases of 7% resp. 7.5% were achieved in simulations. Further areas of research include the development of a hermetic ejector design including corresponding design tools and simulation models and the experimental validation of ejectors operated under different heat pump conditions. Besides, also more detailed information is required on energy-intensive industrial processes and their detailed characteristics. This work is currently being conducted with a renowned Austrian heat pump manufacturer within a nationally funded research project.

Keywords: decarbonization, high temperature heat pumps; ejector technology; performance increase; replacement of natural gas

1 INTRODUCTION

Decarbonization of industrial energy systems and processes is a challenge to overcome on the way towards sustainable, low-emission, societies. According to IPCC, pathways limiting global warming to 1.5 °C indicate that carbon emissions from industry should decrease 65% down to 90% by 2050 compared to 2010 levels [1]. Industrial heat pumps allow for waste heat recovery and the climate-friendly supply of process heat. They are important for Austria as business location for two reasons: firstly, they allow deep decarbonization of industrial heat process, as they cause up to 70% less carbon emissions than conventional natural gas boilers. Secondly, more than 30% of heat pumps produced in Austria are exported [2].

Heat pumps are well established for domestic heating and hot water preparation. Their use in industrial processes is in a rather early stage of market diffusion. In 2021, around 480 industrial heat pumps are operated in Austria with increasing sales numbers in the last years

[2]. 69 use cases have been collected in the IEA HPT Annex 48 project with most applications in the food sector [3].

A study by Geyer et al. [4] indicates large potential for industrial heat pumps within Austrian pulp & paper, chemical and food industries. Research by Marina et al. [5] on process level shows, that in these industries most waste heat potential is available at source temperatures up to 60°C whereas process heat is mainly required at supply temperatures above 100°C. In the last years substantial technological progress has been made and technical barriers have been overcome. Work in the IEA HPT Annex 58 [6] shows an overview of 34 high temperature heat pump systems of 29 manufacturers enabling heat sink temperatures above 100°C.

High temperature lifts usually come with a high condenser pressure and thus losses in the expansion process taking place in an isenthalpic throttle valve. Theoretical research work indicate that ejectors first described for the use in heat pumps in 1931 [7] are innovative components which allow the recuperation of some of the expansion energy leading to substantial increases in efficiency. According to Lawrence and Elbel [8] an increase in efficiency of up to 27% compared to conventional heat pump systems is achievable.

In this paper, results of a national study aiming at assessing the technical feasibility of ejector technologies in industrial heat pump applications are presented focussing on two industrial use cases: industrial steam production at 130°C and industrial drying at supply temperatures of 160°C.

2 METHODS

2.1 Simulations on ejector level

An ejector is a technical device for mixing and expanding two fluids, whereby one fluid, the high-pressure fluid, is accelerated and the other fluid, the low-pressure fluid, is entrained in a free jet. Upstream of the ejector outlet, a pressure recovery is realised using a diffuser. Figure 2-1 shows an ejector with its components and mode of operation in a simplified way.

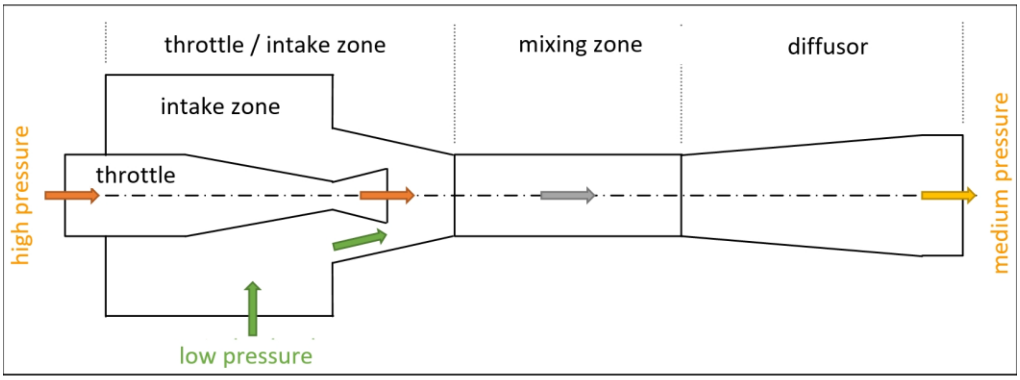


Figure 2-1: Schematic representation of an ejector (adapted from [9], [10])

The use of ejectors has been proposed for a variety of heat pump working fluids [11]. Butane has shown outstanding properties and economic potential in a prior research project [12] and is therefore used in this study for the simulation of two-phase ejectors.

To thoroughly assess the flow processes in an ejector driven by butane as working fluid, CFD simulations were carried out using a commercial software tool. The simulations are based on a homogeneous model to ensure sufficiently short calculation times when simulating different ejector geometries and heat pump operating conditions. The model chosen simplifies the flow in the ejector as a homogeneous mixture and therefore is described by Navier-Stokes equations in a single-phase formulation. It was largely adopted from [13] and is extendable to include thermodynamic inertias (metastable effects) along the lines of [14] if required.

Ansys Fluent® was extended for enabling the simulation of a two-phase flow. Besides, its temperature-based energy equation was replaced by an enthalpy-based one to allow the application of the equation also in the two-phase region. All material data such as density, viscosity or specific heat capacity are defined as a function of pressure and enthalpy, as these can be determined regardless of whether the fluid is supercooled, superheated or in the two-phase region. Using user defined functions (UDFs), two-dimensional look-up tables are created for this purpose, which contain material data from the open-source material data library as a function of pressure and enthalpy. Material properties are determined from these look-up tables by bilinear interpolation.

The Reynolds stress tensor, which occurs in the Reynolds averaged Navier-Stokes equations (RANS), was modelled by an eddy viscosity model to consider turbulences. The k-ω SST model was chosen for this purpose. To allow for efficient simulation of different ejector geometries, a parameterised ejector geometry model was established, on which all dimensions are freely adjustable. A two-dimensional, axisymmetric computational mesh was automatically created from this model. It consists of quadrilateral cells only, is conformal, of the highest quality in terms of aspect ratio and skewness and has the cell density near the wall (y+ < 5) necessary for the k-ω SST turbulence model used. Since the flow in the ejector is supersonic and compression shocks occur, and at the same time the density can experience jumps of two orders of magnitude with a sufficient pressure change in the two-phase region, a calculation strategy was developed to secure reliable results.

2.2 Simulations of heat pump configurations

Among others, we identified three promising options for integrating an ejector into the refrigeration circuit of a heat pump as depicted in Figure 2-2 and described in more detail in [8].

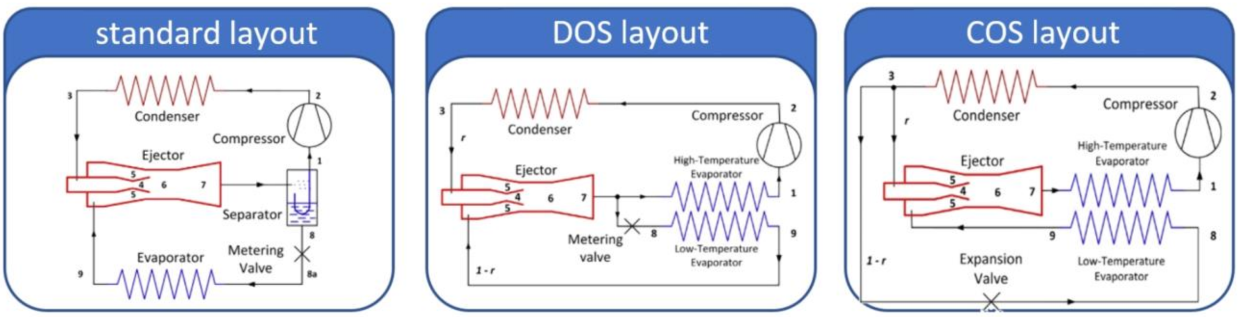


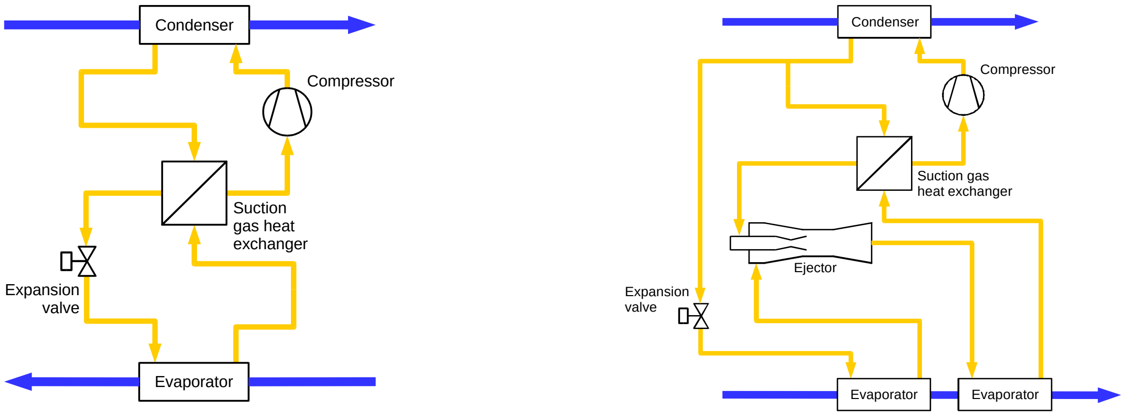
Figure 2-2: Possibilities of integrating ejectors in refrigeration circuits [8]

Out of those three possibilities, the Condenser Outlet Split (in short COS) ejector circuit was identified as most promising solution und evaluated further. It includes two condensing temperatures which enables the use of two heat sources with varying temperatures. However, the efficiency of the refrigeration circuit is largely dependent on the interaction of ejector and compressor characteristics.

Table 2-1: Advantages and Disadvantages of the integration

	Standard	DOS	COS
Advantages	• Good refrigerant distribution • Pressure reduction in condenser • Good heat transfer	• Advantageous ejector characteristics	• Advantageous ejector characteristics • Circulation of oil
		• Two condensing temperatures	• Two condensing temperatures
Disadvantages	• Separator required • Disadvantaged ejector characteristics • Circulation of oil	• Circulation of oil	

As reference heat pump configuration for the simulation of operating conditions, a closed refrigerant circuit with a single-stage compression and the option of integrating a suction gas superheater was chosen (see Figure 2-3).



a) Reference refrigeration circuit ***b) Ejector - COS***

Figure 2-3: Heat pump configurations chosen for simulations

For common heat pump components such as e.g., heat exchangers, proven models from commercial libraries for the dynamic simulation environment were used. The compressor model was parameterised using knowledge from other research projects with a pressure ratio depending on characteristics in the form of volumetric and isentropic efficiency. The ejector model used for system simulations is based on test bench measurements [15] and from experimental results from industrial environment [16]. These data were supplemented with empirical measurement data from literature, whereby correlations from mass flow entrainment ratio and pressure recovery were used.

In the course of the evaluation of the results, stationary operating points are compared with each other. However, the selected simulation environment Dymola/Modelica is a dynamic environment that can be equipped with continuous controllers. In that way, the same control strategy is implemented in the model as in the real heat pump. Based on a simple heat pump circuit, the relevant control tasks are, on the one hand, the correct conditioning of the refrigerant at the compressor inlet and, on the other hand, the capacity control through the compressor speed.

For most of the heat pump circuits with ejectors, the ejector characteristic in interaction with the compressor characteristic plays a decisive role. If we look at the ejector standard variant shown in Figure 2-2 (left), it has a decisive disadvantage compared to the other two variants. In this case, the ejector characteristics in the form of the entrainment ratio must exactly match the vapor content at the ejector outlet so that the level in the separator remains constant and there is no overflowing with liquid or sucking empty of vapor. One can now either accept a limited operating range with a constant superheat of 5K in the evaporator, or realize a variable superheat in the evaporator, which will lead to efficiency losses as the evaporating temperature decreases. In terms of control mechanisms, the selected ejector COS variant is the most robust. Here, the ejector characteristic plays a subordinate role because this configuration can be operated as a simple refrigeration circuit in the case when the ejector is not functioning properly. The control strategies implemented are depicted in Table 2-2.

Table 2-2: Control strategies of the model

Component	Setpoint	Controlled variable
Compressor	Heat output	Speed
Expansion valve	Superheat after evaporator	Valve position
Admixing valve on suction gas superheater	Superheat after compressor	Valve position

In order to compare the reference configuration with the COS ejector configuration, steady-state simulations were carried out at different operating points resulting from the temperature range of the two selected use cases. Further, the heat source is either cooled down by 5K or 10K. Table 2-3 depicts the parameters used for the numerical comparison of the heat pump configurations for the two use cases industrial steam production and industrial drying.

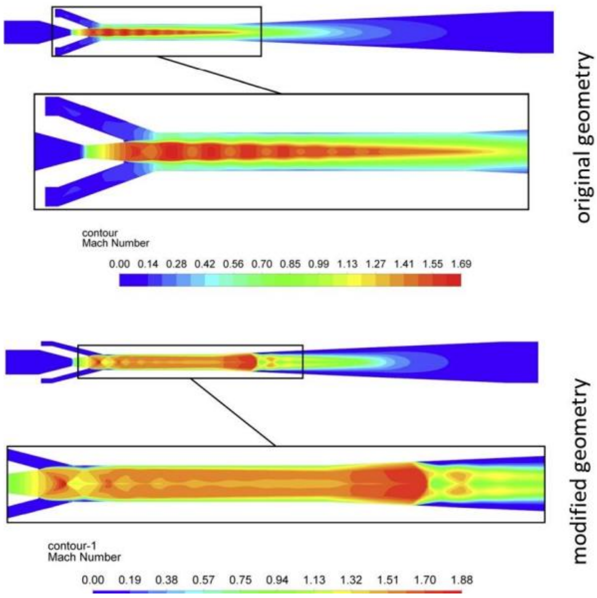
Table 2-3: Parameters applied

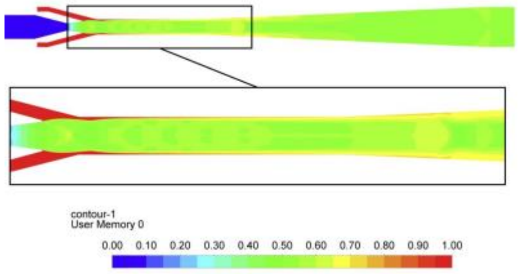
Use case	Refrigerant	Heat source	Heat sink	Source cooling
Industrial steam production	R600	60 – 100°C	130°C	5 resp. 10 K
Industrial drying	R1336mzz-Z	60 – 100°C	160°C	5 resp. 10 K

3 RESULTS & DISCUSSION

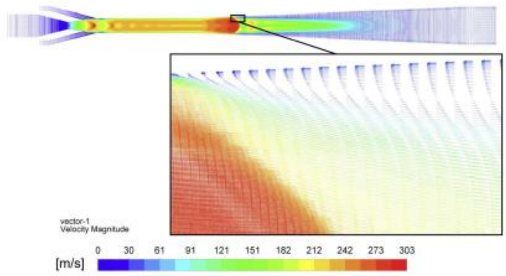
3.1 Results from simulations on ejector level

The CFD simulations performed showed that already small deviations in the ejector geometry can have large effects on the flow phenomena. Small changes applied to the geometry led to a higher flow velocity (visualized by the Mach number) and the flow remained supersonic until the diffuser entrance region, where a supersonic shock occurred (see Figure 3-1, a). This led to a flow boundary layer separation and recirculation region at the entrance region of the diffuser (Figure 3-1, c). The ejector’s nozzle develops a sharp interface between the primary and secondary flow (Figure 3-1. b), whereas the two streams mix in the mixing zone and the interface becomes more diffuse with a nearly homogeneous distribution of steam quality as it enters the diffuser at the original geometry.





b) Comparison of vapor quality



a) Comparison of the Mach number

c) Velocity vectors within the ejector geometry (coloured with the velocity magnitude for the modified geometry).

Figure 3-1: Results from CFD work on component level

3.2 Results from simulations of heat pump configurations

Subsequent figures 3-2 and 3-3 show selected results from the steady-state circuit simulations carried out at different operating points to compare the two refrigeration circuits for two use cases, industrial steam production at supply temperatures of 130°C and industrial drying at 160°C in terms of changes in coefficient of performance (COP) and heating capacity.

As evident, in both use cases the ejector circuit provides no significant advantage over the reference circuit at a source cooling of 5K (depicted in both figures on the left). The low level of cooling negatively influences the functioning of the ejector, as it is "locked" into the low-pressure difference between the two evaporators. However, the results also show the advantages of the COS circuit. Although the boundary conditions for the use of the ejector are suboptimal (5K source cooling), the refrigeration circuit can still be operated in a single-stage design without loss of efficiency or heating performance. If the source cooling doubles from 5 to 10K (as shown in both figures on the right), the ejector characteristics show a positive effect at the prevailing pressure difference between the two evaporators and both, heating capacity and COP increase compared to the reference circuit.

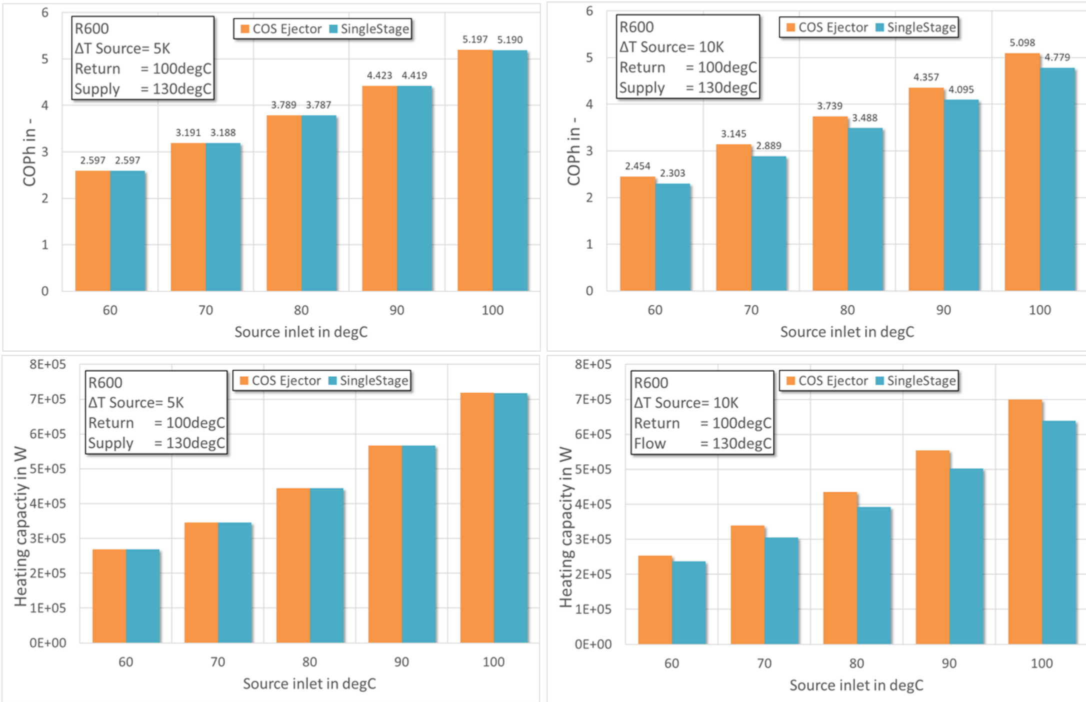


Figure 3-2: Results for industrial steam production at 130°C with R600
(left: 5K cooling of source, right: 10K cooling of source)

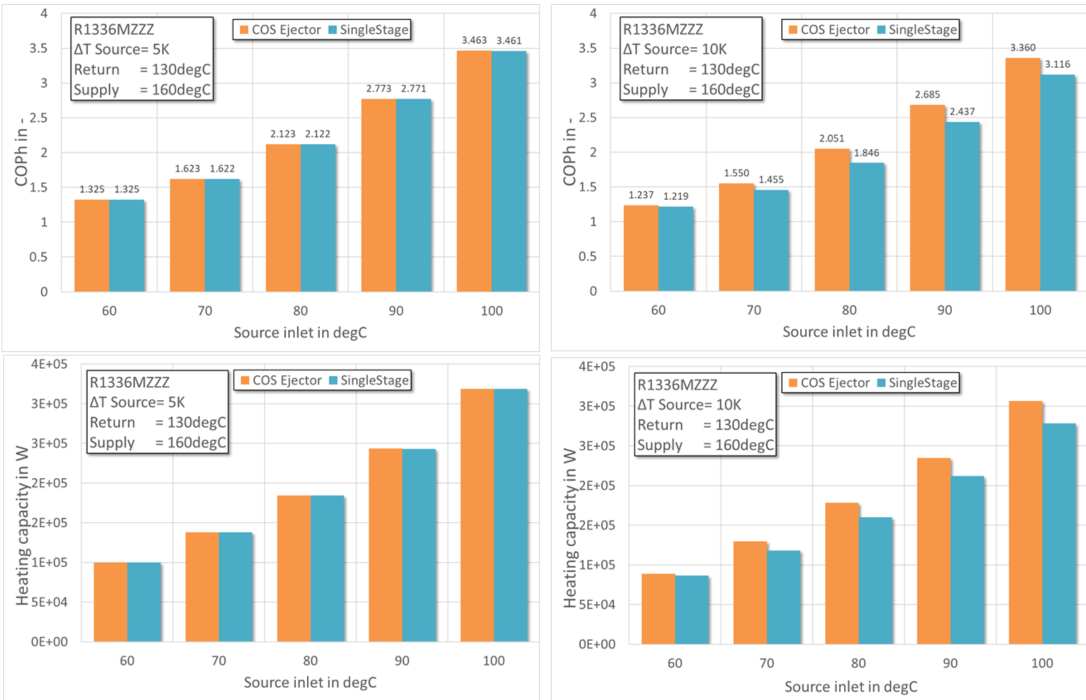


Figure 3-3: Results for industrial drying at 160°C with R1336mzz-Z
(left: 5K cooling of source; right: 10K cooling of source)

For both industrial applications, the maximum increase in efficiency (COP) and heating capacity is to be harvested in the middle range of the source temperature, i.e. 70° to 90°C. Here, compressor and ejector characteristics complement each other best. For industrial steam generation, the average increase in heating capacity is approx. 10%, that of the COP approx. 7%. For drying, the average increase in heating capacity is 9%, while that of the COP is 7.5% and thus in a similar order of magnitude than for steam generation. Positive upward outliers are seen at source temperatures of 80°-90°C, where both increases are over 10%. It was shown that the ejector has no technical disadvantages compared to heat pumps without ejector, even under less favourable operating conditions, and that the COP is unchanged.

4 CONCLUSION & OUTLOOK

Ejectors proved to be feasible to partially recover the expansion work in heat pumps to be used in industrial applications such as industrial drying and steam production with large temperature lifts needed. Further areas of research include especially the development of a hermetic ejector design, experimental validation of ejectors operated under different heat pump conditions, the further development of models for simulation and the development of tools for an efficient ejector design. Besides, also more information is required on energy-intensive industrial processes and their detailed characteristics in terms of demand for process heat (temperatures and heat quantity) and availability of waste heat sources (temperatures and heat quantity). This work is currently being conducted with a renowned Austrian heat pump manufacturer within the nationally funded research project ETHP - Ejektortechnologien für Wärmepumpen (FFG project number FO999888433).

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] V. Masson-Delmotte, et al., "Summary for Policy makers", Global warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24, [Online]. https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SPM_version_report_LR.pdf (Accessed on 05.08.2022).

[2] P. Biermayr, et al., „Innovative Energietechnologien in Österreich, Marktentwicklung 2021“, Berichte aus Energie- und Umweltforschung, 21b/2022, [Online]. https://nachhaltigwirtschaften.at/resources/iea_pdf/schriftenreihe-2022-21b-marktstatistik-2021-web.pdf (Accessed on 05.08.2022).

[3] R.M. Jakobs, C Stadtländer, „Final Report Annex 48: Industrial Heat Pumps, Second Phase", February 2021, [Online]. https://heatpumpingtechnologies.org/publications/final-report-annex-48-industrial-heat-pumps-second-phase/ (Accessed on 05.08.2022).

[4] R. Geyer, et al., „IndustRiES, Energieinfrastruktur für 100 % Erneuerbare Energie in der Industrie, BMVIT, Wien, 2019“, [Online]. https://www.klimafonds.gv.at/wp-content/uploads/sites/16/Studie_IndustRiES-2019_neu.pdf (Accessed on 05.08.2022).

[5] A. Marina, S. Spoelstra, H.A. Zondag, A.K. Wemmers, “An estimation of the European industrial heat pump market potential”, Renewable and Sustainable Energy Reviews, Volume 139, 2021.

[6] IEA HPT Annex 58, [Online]. https://heatpumpingtechnologies.org/ (Accessed on 10.08.2022).

[7] N.H. Gay, “Refrigerating System”. U.S. Patent US1836318A, 15.Dezember 1931.

[8] N. Lawrence, S. Elbel, “Theoretical and practical comparison of two-phase ejector refrigeration cycles including First and Second Law analysis”. International Journal of Refrigeration, Vol 36 (2013), pp. 1220-1232, 2013.

[9] K. Banasiak, et al., “A CFD-based investigation of the energy performance of two-phase R744 ejectors to recover the expansion work in refrigeration systems: An irreversibility analysis”, International Journal of Refrigeration, Volume 40 (2014), pp. 328-337, 2014.

[10] K. Banasiak, et al., “Development and performance mapping of a multi ejector expansion work recovery pack for R744 vapour compression units”, International Journal of Refrigeration, Volume 57 (2015), pp. 265-276, 2015.

[11] J. Chen, H. Havton; B. Palm, “Screening of working fluids for the ejector refrigeration system”, International Journal of Refrigeration, Volume 47 (2014), pp. 1-14, 2014.

[12] HighRef project, supported by FFG/KLIEN in the Austrian funding program “New Energies 2020”, FFG no. 834666, 2014-2016.

[13] J. Smolka, Z. Bulinski, A. Fic, Â. Nowak, K. Banasiak, A. Hafner, “A computational model of a transcritical R744 ejector based on a homogeneous real fluid approach”, Applied Mathematical Modelling, Volume 37, pp. 1208-1224, 2013.

[14] J. Bodys; J. Smolka, M. Palacz, J. Haida, K. Banasiak; “Non-equilibrium approach for the simulation of CO2 expansion in two-phase ejector driven by subcritical motive pressure”, International Journal of Refrigeration, Volume 114, pp. 32-46, 2020.

[15] HighButane 2.0 project, supported by FFG/KLIEN in the Austrian funding program “e!Mission 2013”, FFG no. 843935, 2014-2017.

[16] StoreItUp-IF project, supported by FFG/KLIEN in the Austrian funding program “Energy research”, FFG no. 848914, 2015-2019.

HOW TO ENABLE INTERREGIONAL HEAT EXCHANGE? - REVIEW AND ANALYSIS OF BEST PRACTICE EXAMPLES

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Abstract: With the net zero emissions target, the combined share of renewable sources in global DH networks should rise from 8% to 35% within the current decade. Here, long heat transmission networks (HTNs) that are connecting multiple industrial waste heat and other sustainable sources, one or more district heating networks and other major consumers, industrial process heat sinks, and/or heat storages, could play a significant role in future energy systems. HTNs will enable the interregional exchange of heat between different consumers and suppliers which would not be completely possible on a strictly local level. With the integration of seasonal storages and the diversification of the heat supply, the supply risks will be minimized, as dependencies on a single source are reduced. The focus of this paper is to give an overview on best practice examples of heat transmission networks. Therefore, interviews were conducted with relevant stakeholders. The findings of these interviews together with an analysis of the best practice examples are summarized and were clustered by strengths, weaknesses, opportunities and threats (SWOT).

Keywords: heat transmission networks; waste heat; district heating, SWOT analysis; expert interviews; best-practice analysis

1 INTRODUCTION

With space heating and hot water making up around 70% of energy consumption in residential sector in IEA member countries, district heating (DH) is a main factor in the decarbonization of the heating sector. [1]. On the other hand, the industrial sector is worldwide one of the main consumers of energy. In an industrialized country the industrial sector accounts for approximately one third of end energy consumption, of which two third are made up by the energy-intensive industry [2], [3]. One of the key synergies between the DH and the industry sector is the utilization of industrial waste heat in DH networks as well as the supply of (low temperature) process heat to industries via DH networks [4]. However, one of the challenges is, that DH networks not necessarily extend near the location of the waste heat source. Especially large-scale industries are often located outside the city and DH networks are usually concentrated in dense urban areas [5].

Heat transmission networks (HTN) connect multiple industrial waste heat and other sustainable sources, one or more DH networks, industrial process heat sinks, and storages. These interregional networks connect urban consumption centers and waste heat-intensive industrial sites and, in doing so, traverse areas with further heat sources and sinks. In [6] some findings on HTN have been elaborated. In general, the high systemic complexity of HTNs bears great risks and with today's energy mix, a broad use of HTNs is not considered realistic. However, rising energy prices make the use of HTNs more economically attractive. In addition, due to the high number of parties involved, the operation has to be clearly structured and network-specific codes and market rules have to be created. HTNs can offer heat cheaply in summer due to a high feed-in potential and low demand. Thus, temperature can also be increased as losses become less relevant. New heat sinks, such as a [absorption driven] district cooling, industrial process heat, smaller networks or seasonal storage can be supplied in this way.

The focus of this paper is to give an overview on international best practice examples of heat transmission networks and the input from key-stakeholders. The findings of the analysis are summarized and clustered by strengths, weaknesses, opportunities and threats (SWOT).

2 OVERVIEW OF BEST PRACTISES

The collection of best practice examples was done via a literature review and compiled to the best knowledge of the authors but does not claim to be complete. Here, a distinction is made between HTNs and unidirectional transport pipelines (HTP) that transport heat from a single supplier into a single DH network. Although such pipelines do not meet the definition of a HTNs, they were nevertheless included in the collection because conclusions can be drawn about cost and economic efficiency.

As a result, a total of 38 systems were identified, 10 of which were classified as HTNs as defined above. The identified HTP systems are listed in Table 1 with basic information (where available). Section 2.1 presents selected HTN systems with more detailed information (where available) and adds information from interviews with key stakeholders from Denmark and the Netherlands.

Table 1: Overview of selected best practice examples of HTP

Location	Country	Length in km	Thermal Capacity in MW_{th}	Heat Supply in GWh/a	Diameter in mm	Sources
Dürnrohr - St. Pölten	AT	31	50	200	450 / 400	[7], [8]
Hallein-Salzburg	AT	19	7,5	80	200	[8], [9]
Sappi – Graz	AT	11	40	170	400	[10],[11],[12],[13]
Mellach – Graz	AT	19	300	600	650 / 550	[8], [14]
Donawitz - Trofaiach	AT	8,2		32	250	[15]
Arnoldstein - Villach	AT	16	19	100		[16]
Chur-Trimmis	CH	9,2	18	31		[17], [18]
Melnik-Prag	CZ	32	340		1200	[19], [20]
Lippendorf - Leipzig	DE	15	300	900	800	[21], [22]
Mannheim - Speyer	DE	21,2	48			[21]
Aachen	DE	20	85			[21]
Boxberg - Weißwasser	DE	16	40		400	[23]
Zolling-Airport Munich	DE	28	150		500 -350	[24]
Viborg	DK	12	58			[21]
Kozani	EL	16,5	137		500	[21]
Helsinki	FI	20	490		1.000	[21]
Turku	FI	25	340		800	[21]
Akranes	IS	62	60		400	[21]
Nesjavellir - Riykjavik	IS	27	290		800	[21]
Rozenburg - Rotterdam	NL	16,8	160		700	[25]
Tilburg	NL	25	170		500	[21]
Diemen - Almere	NL	8,5	260		700	[21]
Almere	NL	10	170		500	[21]
Oslo	NO	13	275		600	[21]
Oradea	RO	86,3	546			[21]
Linkoping - Mjolby	SE	28	25			[21]
Lindesberg	SE	17	26			[21]
Gothenburg - Kungälv	SE	22	19			[21]

2.1 Selected examples of long heat transmission networks (HTN)

2.1.1 Austria

Location	Operator	Special Feature	Length in km	Thermal Capacity in MW_{th}	Heat Supply in GWh/a	Diameter in mm
Pöls - Judenburg Heat pipe Aichfeld	Bioenergie Aichfeld GmbH	Multiple DHN and directly connected large consumers	18	30	100	300 / 250

In the region of Judenburg, Fohnsdorf and Zeltweg, there are several DH networks which have been connected to a common DH pipeline supplied by waste heat from the pulp manufacturer since 2012, as investments in new technologies have created a significant amount of surplus heat. In addition to the large industrial waste heat supplier and several DH networks, biomass heating plants and large customers are also connected to the transmission line. [26], [8], [27]

<table>
<tr><th>Location</th><th>Operator</th><th>Special Feature</th><th>Length in km</th><th>Thermal Capacity in MW_{th}</th><th>Heat Supply in GWh/a</th><th>Diameter in mm</th></tr>
<tr><td>Innsbruck-Wattens</td><td>TIGAS, Hall AG, IKB</td><td>Many distributed suppliers and small-scale sinks</td><td>20</td><td></td><td>147,5</td><td></td></tr>
<tr><td colspan="7">Since 2012, the DH network in Innsbruck has been connected to the network in Wattens via a DH transmission network. The transmission network enables better utilization of existing supplier infrastructure as well as the integration of previously unused industrial waste heat (paper mill and foundry) along the route and has the advantage that a possible failure of one system can be compensated very easily. The supply structure is in general highly distributed. There is a partial separation between transmission system operator and distribution system operator. Along the route, in addition to large industrial waste heat sources, several biomass plants, a sewage treatment plant and natural gas boilers are connected. [28], [29]</td></tr>
</table>

2.1.2 Germany

<table>
<tr><th>Location</th><th>Operator</th><th>Special Feature</th><th>Length in km</th><th>Thermal Capacity in MW_{th}</th><th>Heat Supply in GWh/a</th><th>Diameter in mm</th></tr>
<tr><td>Niederrhein</td><td>joint company (Dinslaken +Duisburg municipal utilities)</td><td>high share of renewable sources; primary energy factor <1%</td><td>40</td><td>550</td><td>786</td><td>400</td></tr>
<tr><td colspan="7">The Niederrhein DH transmission network was built between 1980 and 1983 and enabled industrial waste heat to be used on a large scale. The network connects the municipalities of Voerde, Dinslaken, Duisburg and Moers and feeds into distribution networks of local DH networks. In addition to renewable and fossil heating plants and CHP units, industrial waste heat from steel production and the chemical industry is also fed into the DH network. [24], [30]</td></tr>
<tr><td>Ruhr</td><td>STEAG GmbH</td><td>first interregional DH network and first network supplied by CHP in Germany</td><td>42</td><td>430</td><td>1600</td><td>800 - 300</td></tr>
<tr><td colspan="7">The Ruhr DH network was commissioned in 1978 and connects the distribution networks of Bottrop, Essen, Gelsenkirchen and Herten. The transmission network and the connected distribution networks are operated by STEAG Fernwärme. Much of the heat fed into the rail system comes from the Herne coal-fired power plant. This is to be taken off the grid in the fall of 2022 and replaced by a new combined-cycle gas turbine power plant, which is expected to result in annual CO2 savings of around 70,000 tons. In the future, further heat sources are to be developed in the area of industrial waste heat. [24], [31], [32]</td></tr>
<tr><td>Saar</td><td>Fernwärme-Verbund Saar GmbH</td><td>central energy control center, thermal storage for peak loads</td><td>35</td><td>686</td><td>943</td><td>600 / 500</td></tr>
<tr><td colspan="7">The Saar DH line was designed in 1973, to secure the energy supply via local infrastructure. The first part of the Saar DH line was put into operation by Fernwärme-Verbund Saar GmbH at the end of 1979. Today, it connects the towns of Dillingen, Saarlouis, Völklingen and Saarbrücken. The largest supplier is a CHP and a gas engine. In addition, waste heat from industry is used. A heat storage with a volume of 22,800 m³ is installed to cover peak loads. In addition to supplying its own distribution networks, the company also supplies the networks of local municipal utilities and directly supplies large consumers. [24], [33], [34], [35]</td></tr>
</table>

2.1.3 Denmark

<table>
<tr><th>Location</th><th>Operator</th><th>Special Feature</th><th>Length in km</th><th>Thermal Capacity in MW_{th}</th><th>Heat Supply in GWh/a</th><th>Diameter in mm</th></tr>
<tr><td>Triangle Region Denmark</td><td>TVIS</td><td>innovative pricing model; process heat customers supplied by the grid</td><td>123</td><td></td><td>1658</td><td>660 - 220</td></tr>
<tr><td colspan="7">The operator of the transmission network in the Triangle region, TVIS, which is a non-profit organisation, was founded in 1983, as a cooperation of the four municipalities connected to the network, Fredericia, Kolding, Middelfart and Vejle. The first stage of expansion of the network was completed in 1987. The reason for building the network was the desire to provide an environmentally friendly and price-stable heat supply for the municipalities. With the transmission network, waste heat from a large refinery, a biomass power plant, which provides the main share of heat and a waste incineration plant could be used. The heat price consists of a fixed and a variable part to adjust to the seasonality of the heat demand as well as a component related to the return temperature. The network already includes a process heat customer, which is supplied. In the future, the waste heat of an electrolyzer will be included in the grid. [36], [37], [38].</td></tr>
<tr><td>Copenhagen</td><td>CTR, VEKS, Vestforbr-ænding</td><td>Load management; 3 transmission networks connected</td><td>189</td><td></td><td>8000</td><td></td></tr>
<tr><td colspan="7">The DH network in the Copenhagen region was established after the introduction of the Heat Supply Act in the 1980s. The municipalities in the region established two companies to ensure the transport of heat from the large central CHPs to the individual distribution networks: CTR and VEKS. The network was continuously expanded and the burning of coal was gradually replaced by increased use of gas and biomass. The transmission networks are interconnected, allowing optimized exchange of heat. Heat is sold to all supplied municipalities at a uniform pool price. This consists of a variable and a fixed component to account for seasonal fluctuations. In order to guarantee the cost-optimal use of the generation plants in the entire Copenhagen interconnected grid, the companies CTR, VEKS and HOFOR have together started a cooperation on load management, which enables a day-ahead and intra-day market for the heat suppliers, analogous to the electricity markets [39], [40], [41], [42], [43]</td></tr>
<tr><td>DH Fyn</td><td>Fjernvarme Fyn</td><td>Several small-scale industrial heat sources included; waste heat of a data center can be integrated via heat pump</td><td>120</td><td>950</td><td>3600</td><td></td></tr>
<tr><td colspan="7">The DH network on Funen around the city of Odense. In an effort to replace coal completely, olive pellets, originating from olive oil production in Spain are imported. Additionally, a focus is placed on industrial waste heat. The waste heat of a data center built in 2020 can be fed into the grid via heat pumps. The heat pump station was built by Fjernvarme Fyn and offers the possibility to integrate further waste into the grid. [44], [45], [46], [47]</td></tr>
</table>

<table>
<tr><th>Location</th><th>Operator</th><th>Special Feature</th><th>Length in km</th><th>Thermal Capacity in MW_{th}</th><th>Heat Supply in GWh/a</th><th>Diameter in mm</th></tr>
<tr><td>DH Aarhus</td><td>Affald-Varme Aarhus</td><td>High investments and efforts for decarbonization; high share of biomass CHP (>70%); fossil share <1%</td><td></td><td></td><td>3100</td><td></td></tr>
<tr><td colspan="7">DH in Aarhus has also emerged from the energy crisis of 1973. In 1985 a new transmission line connected the heat supply of Aarhus. A main advantage is the higher security of supply. Over the past 10 years, investments of more than $270 million have been made to decarbonize Aarhus' DH system. This has involved installing an 80 MW electrically heated boiler, converting a 540 MW coal CHP to wood pellets, building a new 80 MW biomass CHP, and constructing 24 MW heat pumps that use seawater as a heat source. [48]</td></tr>
</table>

For a more detailed analyses of the HTNs in Denmark, interviews have been performed with one operator of a HTN, and a representative of the DH association from Denmark, that can be summarized as follows:

Financing and business cases for long transmission networks: The large DH systems in Denmark emerged from the energy crisis of the 1970s, when the heating market was heavily dominated by expensive imported oil. Policymakers then promoted the use of industrial waste heat to supply heat to residential buildings. At the time of the planning of the transmission network in the 80's, the participating municipalities could only raise about 0.2% of their own funds for financing. A company was formed in which each municipality was liable for the entire debt. In this way, some international financiers could be attracted. In order to guarantee repayment within 20 years, the heat price was adjusted annually. Decisive factors for the establishment of DH transmission networks were the familiarity of the technology, the lack of private-sector interests, the agglomeration of urban and rural heat suppliers that do not produce at maximum capacity, the low-cost laying of pipes over agricultural land, and the possibility of price advantages in connecting networks and optimized use of combined production capacities. Financing and business model are based, among other things, on a tax increase on other fuels (electricity, gas...) in order to make more attractive the injection of CHP, waste incineration and industrial waste heat, on the lack of profit motive of operators and the interconnection of individual networks to increase cost-optimized heat production.

Cost structure for customers of long transmission networks: All distribution systems connected to the transmission network purchase heat from it at the same price. Since some systems operate with hourly prices, different load profiles of the distribution networks lead to different prices. In addition, there is a financial incentive to redirect the return temperature in the distribution network by making better use of the heat flow.

Industrial waste heat integration: While the supply of industrial waste heat is common in Denmark, the supply of process heat through a DH network is rare. Due to the lack of heavy industry in Denmark, the potential is rather low. Coupling of heating and cooling networks that can be used as heat sinks in summer is also not common. In order to protect the interests of the industry as well as the non-profit network operator regarding waste heat integration, the project was divided into 3 phases. In phase 1, the network operator pays the industry the substitution price of the network (price of the most expensive supplier). In phase 2, all profit goes to the network operator. In phase 3, the profits are divided according to the investments made by the partners. Decisive for success were mutual trust, open communication or calculation, and the division of the project into 3 phases.

Heating market: Varmelast was launched to curb the monopoly position of the large heat producers in Copenhagen. Varmelast enables load control of the heat network by means of the heat market, in which waste incineration plants participate in addition to the large CHPs. The producers submit their bids, the determined schedules are prepared every morning and adjusted four times a day.

Risk assessment, decarbonization and challenges: As the size of the network increases, the dependence on individual feeders decreases and thus the security of supply increases. Due to the diversified producer structure, the heat from the transmission network is independent of the price structure of a fuel (gas, electricity...). This provides price stability. With a well-developed DH system, decarbonization of a few sources is easier than retrofitting many individual systems. The investment decisions in a new transmission network, due to the decentralization of suppliers, is a major challenge in view of the upheavals in the energy system. The shift from large, central suppliers to smaller, decentralized suppliers also poses a great challenge for the control of the system.

2.1.4 Netherlands

Location	Operator	Special Feature	Length in km	Thermal Capacity in MW_{th}	Heat Supply in GWh/a	Diameter in mm
Rotterdem - Den Haag (planned)	Gasunie	Industrial waste heat from port of Rotterdam; geothermal potential will be integrated	23	250		700
To replace natural gas as the most important energy source for providing heat in buildings in the Netherlands, a plan has been developed for an extensive sustainable heating system in South Holland. As part of this heating system, the WarmtelinQ project will connect the DH network of The Hague with the network of Rotterdam starting in 2023. For this purpose, an underground pipeline will be built, connecting to an existing transport pipeline from the port of Rotterdam to the center of Rotterdam. The pipeline is being built and operated as an open network by the state network operator Gasunie. This means that the pipeline will be made available to all parties wishing to use it on the same terms. The supply of heat to end users is the responsibility of the energy suppliers. Waste heat from the port of Rotterdam is to be used primarily as heat sources. In the future, local geothermal potentials are also to be tapped as heat sources. [49]						

The Netherlands are one of the few countries, where a new HTN is planned to be build, so an interview has been done with a consultancy who did a detailed study on the prospective HTN. The interview can be summarized as follows:

Regional heat plan for South Holland: The Port of Rotterdam, the City of The Hague and surrounding are working on a large, interconnected heating network. Since the planning of a comprehensive heat network is complex, taking into account heat and temperature requirements, demand structure, route for pipelines, optimal merit order, hydraulics, etc., a comprehensive model was developed to represent this system as a digital twin.

Scenario analysis of the large, interconnected heat network (backbone): At the moment, the heat demand is currently mostly met from fossil sources. Possible heat sources include: Waste heat (Rotterdam port, hydrogen production, low temperature waste heat) and geothermal energy. The possible heat sinks include: Local heating networks (some need to be newly built). It was clear in the analysis, that the economic viability of the backbone depends on the number of heat customers. The analysis also considered of different scenarios, such as a “Maximum scenario”: Heating demand covered by renewable heat from backbone, a “Isolated solution”: All distribution networks individually tap suitable heat sources as well as an “optimal approach” lies in between (stranded assets have to be avoided).

WarmtelinQ: The connection between the port of Rotterdam to The Hague should be implemented with the WarmtelinQ project. For optimal planning, a digital twin is used to simulate the system in minute resolution. The digital twin will continue to be used in operation after the pipeline is completed to ensure optimal load control (heat merit order) and hydraulic integrity. Different risks has been identifies for the project, such as the short term utilization rate of the pipeline and its future development , the connection rates of new customers as well as the coverage of peak load capacities to be provided locally as a priority.

3 EVALUATION

3.1 Quantitative comparison

The identifies HTPs and HTN are analyzed in terms of key parameters. As it can be concluded from Table 2 below, HTNs are generally longer compared to HTPs. The average heat delivery of HTNs varies by a factor of about 8 compared to HTPs.

Table 2: Overview of the average properties of THNs and HTPs

Parameter	Average	HTN	HTP
Distance in km	32.3	62.2	22.7
Capacity in MW_{th}	221.8	482.7	163.8
Heat delivery in GWh_{th}/a	1422.1	2302.3	264.1
Specific investment cost in €/m	725.3	816.6	699.2
Linear power density in MW/km	8.8	10.7	8.4
Linear heat density in MWh/m·a	21.6	24.8	16.4

According to Figure 3-1, the relation between the supplied heat in HTNs (red squares) and the network length can be approximated by a rising power function with an exponent of about 1.75. HTPs (blue dots) do not follow a specific trend; Parameters of HTPs with lengths below 20 km vary to a larger extent. This graph shows that the specific amount of heat in GWh transported per kilometer is decreasing with increasing network length. This could lead to the conclusion that with less heat transported, less profit is generated by the DH network. This does not fit together with the “economy of scale” approach, where a system will become more profitable with increasing size. Further research has to be conducted to answer this trend.

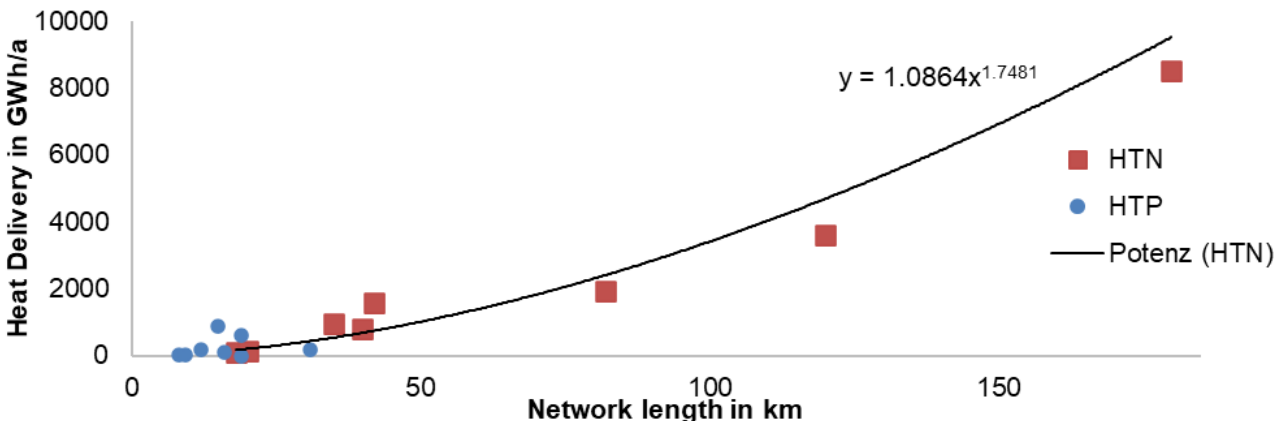

Figure 3-1: Comparison of supplied heat and network length for HTN and HTP

3.2 SWOT Analysis

Based on the findings from the literature review and interviews, an analysis of the strengths, weaknesses, opportunities, and threats (SWOT analysis) on HTNs was conducted, see Table 3.

Table 3: SWOT Analysis on long heat transfer networks1

Strengths • Enables optimal integration and utilization of regionally available heat sources that are not located directly nearby DH areas • Possibility of providing heating to customers outside metropolitan areas • Less dependence on individual suppliers due to the large number of connected suppliers; diversification of the heat supplier technologies used • Interconnection of individual networks enables cost-optimized heat supply, i.e. only the production plants with the lowest heat generation costs are operated • Resilient and price-stable heat supply for the connected communities possible • Promoting cooperation between municipalities and the optimal use of existing resources	**Weaknesses** • High infrastructure investment costs • High complexity, resulting in higher effort for planning and operation • High inertia for changes in system parameters (e.g. temperature changes) • a reduction of system temperatures in the HTN is only possible with corresponding changes in the distribution networks • Provision of peak load should be done at local level of distribution networks to keep peak load capacity in transmission network low, thus reducing variable heat costs • High need for coordination between different stakeholders: Heat suppliers, transport network operators and distribution network operators
Opportunities • Affordable land for the integration of (seasonal) heat storage more likely available along the pathway of the HTN than in urban DH networks • Political commitment and correspondingly conducive legal and regulatory framework (e.g., tax reductions, subsidies for connection	**Threats** • Utilization rate of the transmission pipeline and its future development are key parameters and may vary, depending on retrofitting rates, the will of local decision makers and other factors • Challenging investment decisions for new infrastructure in view of the general

[1] This SWOT analysis is not including factors related to DH in general, or to individual supply options, like waste heat; it is focussing specifically on factors related to HTNs

costs, connection obligations, etc.) promote the development and economic viability of infrastructure • Many participants could enable the establishment of a heat market analogous to the electricity market for the cost-optimal use of existing heat sources • Unstable energy prices favor the large-scale utilization of alternative heat sources; and HTN are sometimes the only possibility to use them efficiently in urban areas.	transition trends in the energy system (tendency for shifting from large centralized to small, decentralized and individual systems)

4 SUMMARY AND CONCLUSIONS

Within this paper, an assessment of international best practice examples regarding heat transmission networks (HTN) has been done. Based on literature research and interviews a SWOT – analysis was conducted.

Interest in HTNs is increasing nowadays, due to rising energy prices and several working examples. Larger networks, including seasonal storages and backup boilers can reduce supply risks and lead to price stability, due to a diversification of the heat supply portfolio.

Outlook: To further push the realization of HTNs in Austria, within the “HeatHighway” project different case studies are investigated. One of them is the Tyrolean “Inn valley”, where the potential is investigated of extending the existing HTN Innsbruck – Wattens towards the east. Literature research is conducted to identify potential heat sinks and sources today and in the future [50]. With the involvement of local stakeholders, the concept of the HTN east of Wattens will be evaluated. This will lead to a basic route and the concept will be evaluated with a techno-economic feasibility analysis.

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6 REFERENCES

[1] ‘District heating needs flexibility to navigate the energy transition – Analysis’, *IEA*. https://www.iea.org/commentaries/district-heating-needs-flexibility-to-navigate-the-energy-transition (accessed Aug. 24, 2022).
[2] ‘Energie in Österreich 2021 - Zahlen, Daten, Fakten’, p. 68.
[3] ‘eia_193_de.pdf’. Accessed: Aug. 24, 2022. [Online]. Available: https://nachhaltigwirtschaften.at/resources/nw_pdf/eia/eia_193_de.pdf
[4] ‘Industrielle Abwärmenutzung. Kurzstudie’, p. 44.
[5] Ralf-Roman Schmidt, Roman Geyer, and Pauline Lucas, ‘DISCUSSION PAPER The barriers to waste heat recovery and how to overcome them?’ Jun. 2020. [Online]. Available:

https://ec.europa.eu/futurium/en/system/files/ged/20200625_discussion_paper_v2_final.pdf

[6] S. Moser and S. Puschnigg, ‘Supra-Regional District Heating Networks: A Missing Infrastructure for a Sustainable Energy System’, *Energies*, vol. 14, no. 12, Art. no. 12, Jan. 2021, doi: 10.3390/en14123380.

[7] ‘Da kommt die Wärme her’, *Fernwärme St. Pölten*. https://www.fernwaerme-stp.at/fernwaerme/da-kommt-die-waerme-her/ (accessed Aug. 29, 2022).

[8] Moritz, Gerhard; Lechner, Herbert; Günter, Pauritsch; Lang, Bernhard; Jamek, Andrea; Zach, Franz, ‘MACHBARKEITSSTUDIE zur Fernwärmetransportleitung St. Veit / Glan – Klagenfurt’, 2013.

[9] ‘Wärmeschiene Hallein - Salzburg mit Energiepreis ausgezeichnet’, *OTS.at*. https://www.ots.at/presseaussendung/OTS_20050512_OTS0152/waermeschiene-hallein-salzburg-mit-energiepreis-ausgezeichnet (accessed Aug. 29, 2022).

[10] ‘Fernwärme aus Gratkorn für Graz: Kooperationsprojekt gestartet’, *MeinBezirk.at*, Nov. 10, 2017. https://www.meinbezirk.at/graz/c-lokales/fernwaerme-aus-gratkorn-fuer-graz-kooperationsprojekt-gestartet_a2312852 (accessed Aug. 29, 2022).

[11] ‘2019-Werk-Gratkorn-Umwelterklärung-(EMAS).pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://cdn-s3.sappi.com/s3fs-public/2019-Werk-Gratkorn-Umwelterkl%C3%A4rung-(EMAS).pdf

[12] admin, ‘Bioenergiegruppe Startseite’, *Bioenergie Gruppe*. https://www.bioenergiegruppe.at/ (accessed Aug. 29, 2022).

[13] ‘Fernwärme in Graz’. https://www.energie-graz.at/egg/news/beitrag/knistern-tut`s-heute-nur-mehr-im-kachelofen (accessed Aug. 30, 2022).

[14] ‘Kraftwerk Mellach wird wieder Fernwärme nach Graz liefern’, *Inside Graz*, Mar. 16, 2021. https://www.inside-graz.at/umwelt/kraftwerk-mellach-fernwaerme-nach-graz-liefern.html (accessed Aug. 29, 2022).

[15] Philipp, ‘Industrielle Abwärme für Trofaiach – Fachverband Gas Wärme’, *Fernwärme*, Nov. 25, 2013. https://www.fernwaerme.at/industrielle-abwaerme-fur-trofaiach (accessed Aug. 29, 2022).

[16] ‘Fernwärmelei-tung von Arnold-stein nach Villach’, Sep. 06, 2018. https://www.5min.at/201809165441/fernwaermeleitung-von-arnoldstein-nach-villach/ (accessed Aug. 29, 2022).

[17] ‘Derungs und Tremp - «Heisses Wasser statt warme Luft».pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://fernwaerme-chur.ch/wp-content/uploads/2021/06/jahresbericht-fernwarme-chur-2020.pdf

[18] ‘jahresbericht-fernwaerme-chur-2019.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://fernwaerme-chur.ch/wp-content/uploads/2020/05/jahresbericht-fernwaerme-chur-2019.pdf

[19] D. Andrews *et al.*, *Background Report on EU-27 District Heating and Cooling Potentials, Barriers, Best Practice and Measures of Promotion*. 2012. doi: 10.2790/47209.

[20] S. Moser and S. Puschnigg, ‘Supra-Regional District Heating Networks: A Missing Infrastructure for a Sustainable Energy System’, *Energies*, vol. 14, no. 12, Art. no. 12, Jan. 2021, doi: 10.3390/en14123380.

[21] K. C. Kavvadias and S. Quoilin, ‘Exploiting waste heat potential by long distance heat transmission: Design considerations and techno-economic assessment’, *Applied Energy*, vol. 216, pp. 452–465, Apr. 2018, doi: 10.1016/j.apenergy.2018.02.080.

[22] ‘Lippendorfer Fernwärme für Leipzig bis 2023’. https://www.stefanschroeter.com/653-lippendorfer-fernwaerme-fuer-leipzig-bis-2023.html#.Ywy_TNPP02x (accessed Aug. 29, 2022).

[23] ‘Stadtwerke Weißwasser - Fernwärme für Weißwasser’. https://www.stadtwerke-weisswasser.de/privatkunden/unternehmen/25jahre/serie-historie-sww/fernwaerme-fuer-weisswasser (accessed Aug. 29, 2022).

[24] ‘EnEff: Wärme Kostengünstiger Fernwärmetransport für den effektiven Ausbau der KWK. Prof. Dr.-Ing. Stefan Holler Statusseminar, 7. - PDF Free Download’. https://docplayer.org/41354452-Eneff-waerme-kostenguenstiger-

fernwaermetransport-fuer-den-effektiven-ausbau-der-kwk-prof-dr-ing-stefan-holler-statusseminar-7.html (accessed Aug. 29, 2022).
[25] ‘Leiding over Noord - Visser & Smit Hanab’. https://www.vshanab.nl/nl/projecten/detail/leiding-over-noord (accessed Aug. 29, 2022).
[26] ‘Energiebericht_Steiermark_2014_.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://www.technik.steiermark.at/cms/dokumente/12678764_146432123/21aa3edf/Energiebericht_Steiermark_2014_.pdf
[27] ‘Q2 - Der Wäremvorteil aus Pöls - Fernwärmeversorgung’. http://www.xn--wrme-vorteil-gcb.at/de-fernwaermeversorgung-2.html (accessed Aug. 29, 2022).
[28] ‘11_hilber_vortrag.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://eventmaker.at/uploads/16600/downloads/11_hilber_vortrag.pdf
[29] ‘tigas_gb20_web_3mb.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://www.tigas.at/uploads/tx_bh/tigas_gb20_web_3mb.pdf?mod=1643036164
[30] ‘Fernwärmeversorgung Niederrhein GmbH - PDF Free Download’. https://docplayer.org/10239000-Fernwaermeversorgung-niederrhein-gmbh.html (accessed Aug. 29, 2022).
[31] ‘Mit STEAG Fernwärme seit über 60 Jahren - PDF Free Download’. https://docplayer.org/213491126-Mit-steag-fernwaerme-seit-ueber-60-jahren.html (accessed Aug. 29, 2022).
[32] ‘Historie’, *Steag Fernwärme*. https://www.steag-fernwaerme.de/de/unternehmen/historie (accessed Aug. 30, 2022).
[33] ‘FVS_Fernwaermeschiene.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://www.fvs.de/uploads/pics/FVS_Fernwaermeschiene.pdf
[34] ‘FVS_Broschuere.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://www.fvs.de/uploads/pics/FVS_Broschuere.pdf
[35] ‘Fernwärme - Verbund Saar GmbH’, *Fernwärme - Verbund Saar GmbH*. https://www.fvs.de/de/ (accessed Aug. 30, 2022).
[36] ‘TVIS | SAMMEN OM VARMEN’. https://www.tvis.net/gron-omstilling/ (accessed Aug. 29, 2022).
[37] ‘TVIS’ Årsberetning 2020 by TVISvarme - Issuu’. https://issuu.com/tonnekjaersvej11/docs/tvis_rsberetning2020 (accessed Aug. 29, 2022).
[38] ‘SAV customers visit Fredericia district heating scheme’. https://www.sav-systems.com/news/sav-customers-visit-fredericia-district-heating-scheme/ (accessed Aug. 29, 2022).
[39] ‘VEKS Aarsberetning 2020 UK.pdf’.
[40] ‘Environmentally-friendly-District-heating-to-Greater-Copenhagen.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://www.ctr.dk/wp-content/uploads/2019/11/Environmentally-friendly-District-heating-to-Greater-Copenhagen.pdf
[41] ‘District-heating-close-up.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: https://www.ctr.dk/wp-content/uploads/2019/11/District-heating-close-up.pdf
[42] S. Vestforbr, ‘50 Ledelsespåtegning 51 Den uafhængige revisors revisionspåtegning’, p. 54, 2021.
[43] ‘DISTRICT HEATING IN COPENHAGEN: ENERGY-EFFICIENT, LOW- CARBON, AND COST-EFFECTIVE - PDF Free Download’. https://docplayer.net/30952939-District-heating-in-copenhagen-energy-efficient-low-carbon-and-cost-effective.html (accessed Aug. 29, 2022).
[44] ‘Hvad er din varme lavet af?’ https://www.fjernvarmefyn.dk/viden/fjernvarme-er-miljoevenligt-nemt-og-billigt/hvad-er-din-varme-lavet-af/ (accessed Aug. 30, 2022).
[45] ‘2_Fjernvarme-Fyn-Heat-Recovery.pdf’. Accessed: Aug. 29, 2022. [Online]. Available: http://grass-events.com/wp-content/uploads/2018/03/2_Fjernvarme-Fyn-Heat-Recovery.pdf

[46] 'Kim_WINTHER_-_FJERNVARME_FYN.pdf'. Accessed: Aug. 29, 2022. [Online]. Available: https://www.ehpcongress.org/archive-2019/wp-content/uploads/Kim_WINTHER_-_FJERNVARME_FYN.pdf

[47] '2_Fjernvarme-Fyn-Heat-Recovery.pdf'. Accessed: Aug. 30, 2022. [Online]. Available: http://grass-events.com/wp-content/uploads/2018/03/2_Fjernvarme-Fyn-Heat-Recovery.pdf

[48] M. B. M. Jensen, 'The Role of District Heating in District Energy', p. 27.

[49] 'Veelgestelde vragen', *WarmtelinQ*. https://www.warmtelinq.nl/veelgestelde-vragen (accessed Aug. 29, 2022).

[50] Nicolas Oliver Marx, Stefan Reuter, and Ralf-Roman Schmidt, 'Heat Highway: Decarbonizing the heating supply via regional district heating networks, Status-Quo for a case study in Tyrol';, presented at the 8th International Conference on Smart Energy Systems, Aalborg, Denmark, Sep. 2022.

[51] 'Heat Highway – Energieinstitut an der Johannes Kepler Universität Linz'. https://energieinstitut-linz.at/portfolio-item/heat_highway/ (accessed Aug. 30, 2022).

GRIDPENGUIN: A DISTRICT HEATING NETWORK SIMULATOR

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Abstract: District heating system (DHS) optimization is becoming an increasingly important problem because of the unused potential in flexibility that could allow less energy being wasted and the integration of renewable energy. While new optimization methods are proposed every year to tackle this problem, the literature lacks a good way to benchmark newly proposed methods. To address this problem, we introduce GridPenguin, an open-source computational simulator for the physics of district heating networks. It provides flexibility in usage by providing building blocks with which the user can build any grid he wants. The detailed simulation of the physical world with a focus on the heat balance and average flow rate and temperature allows for fast and accurate simulation. By explaining the physical equations and computational model as well as the comparison to existing software, we lay a solid foundation for the performance of the simulator. We present GridPenguin as a metric to evaluate optimization methods as well as a tool for easy integration of advanced machine learning methods into DHS optimization. The source code of our project can be found on https://github.com/ftbv/grid-penguin

Keywords: District heating system; Simulation; Optimization; Heat production planning

1 INTRODUCTION

Heat networks can play an important role in the energy transition by reducing the dependency on fossil fuels. Also they can provide flexibility in their use and/or production of electricity, an important feature in the future power system. Currently in many district heating networks, the decisions on heat and power production are often made separately. The decision on heat is made purely based on the experience of the grid operator, and the temperatures are often kept relatively constant throughout a season.

In the literature, various scientific attempts have already been made to empower operators to reduce heat losses and use the flexibility of DHS for electricity balancing using various methods including MILP, NLP and Genetic algorithms [1] [2] [3] [4] [5].

However, to the best of our knowledge, the literature of DHS optimization has two crucial limitations. First, there exists no benchmark to evaluate and compare different papers and methods. A paper proposing a novel method usually evaluates it in the exact same model it uses for optimization, and the proposed method is only compared with simple or traditional strategies instead of other methods from the literature [1] [3] [6]. Second, mathematical optimization methods dominate this field. They require a deep and comprehensive understanding of DHS from the researchers to simplify the complex, non-convex DHS to a solvable linear or convex model. It might be beneficial if less domain knowledge is required and data-driven machine learning methods can be used. However, there is no standard dataset, nor a standard way to generate reliable data. Getting data directly from the grid can be very difficult and is not flexible enough for collecting data for rare situations. On the other hand, we lack a reliable model to generate artificial data that simulates real grid accurately enough.

To address the above-mentioned limitations, we propose GridPenguin: a comprehensive, accurate and still relatively fast simulator of a DHS. Various modules that model components in a DHS are provided to the user, and these modules are backed-up with equations describing the physics of the heat system and the hydraulic system [7]. After the user specifies the grid structure and the production plan, the software will run and provide a detailed grid status at every time window. GridPenguin is proposed as a benchmark to evaluate and compare different optimization methods. The software has a more detailed model of a DHS than most models built for optimization and using it to evaluate the optimization methods provides better insights into the performance of the optimization. It also makes it possible to compare different methods. Second, as it gives users the freedom to build any grid they want, they can use it to generate data for machine learning methods. It is more accessible and flexible than a dataset collected from a real grid and the accuracy is good, compared with existing software on modelling heat/hydraulic grids.

There are a few existing software packages on the market and in the research community that can also model district heating networks. However, they are built with a different focus and have a different functionality and do not meet these goals. Wanda is a powerful software package which models a hydraulic system with good accuracy. Wanda is very accurate in the simulation of hydraulics but less so in heat transfer and heat production. This means it is not ideal for studies of heat networks where simulation of heat is generally more important than hydraulics. Wanda also runs relatively slow. ESSIM/ CHESS is an energy system simulator. At the moment of writing, the source code is not available and we could not find more detailed information about CHESS. DisHeatLab models the pipes and flows in a district heating system, but we could not find detailed models for heat exchangers or various types of producers. This limits the power of an optimizer that works using data from such a simulator. Comsof models the heat grid on high level and in a steady state. It cannot facilitate a detailed, hour-to-hour plan and it is not open-sourced, making it difficult for any self/machine-learning method to interact with it.

The rest of this paper is structured as the following: in Section 2, we give implementation details of the software, including the physical equations describing the behaviors, the computational methods to simulate these equations and the interface of modules of the software. In Section 3 we compare our model with the detailed hydraulic modelling software Wanda, and we show how accurate our model is compared to other similar software: Wanda. In Section 4, we discuss aspects that can be improved and what future work could focus on. Finally, the conclusion is given in Section 5.

2 MODEL IMPLEMENTATION

In this section we explain how the computational model is implemented: what physical relations are considered, how are they simulated computationally and in what order are they computed. With this section we hope to provide the reader a clear overview of what the model can be used for.

2.1 Main design choices

On the one hand, to serve as a benchmarking tool for district heating optimization algorithms, a simulator needs to have good accuracy. On the other hand, the need to use it intensively and repeatedly, as is required for example for machine learning algorithms [8], means it needs to have a decent speed as well. For the trade-off between speed and accuracy, we make the following design choices: 1. We aim to have a highly detailed simulation of heat and temperature. This includes the heat exchanging, heat loss and the production of heat; 2. Time is discretized almost everwhere in GridPenguin. The length of these time steps are specified by the user, for example at 15 minutes or 1 hour. The simulation accuracy should improve with smaller time steps, naturally at the cost of an increase in simulation time; 3. We simulate the pressure and the cost of running pumps in a simplified way for the speed of the simulation. Also, as reported in an earlier study, pressure is insignificant for optimizing the heat grid [7].

To represent the physical grid infrastructure in GridPenguin, we use two types of components: nodes and edges. An edge represents a pipe that is used for water transportation. A node may represent various components, such as a producer (CHP, heat pump, geothermal source, boiler), consumer, junction branch or water pump. Each of these components in GridPenguin is used in every step of the simulation.

In each time step, the computation starts from the consumers, then components that are directly connected to consumers, then components connected to those components. This continues through the whole grid and terminates when reaching the producers. Mass flow propagates through the grid with no time delay and total mass of water in the grid as well as water density is assumed constant.

To run GridPenguin, the following inputs are needed: the heat demand at each consumer (in MW), and the production plan of a producer in either heat production (in MW) or output temperature (in °C). If electricity trading is considered, then also the market electricity price and the electricity production plan (in MW) should be included. After the simulation, the user can obtain the output of almost every physical property that is relevant to a heat network, such as the temperature at any point of the grid, the heat loss in an edge, mass flow, whether production plan is feasible, etc. These values also come in discrete time for each time step. Note that for readability we have omitted the time step subscript in the equations in this section.

2.2 The Edge

The two physical equations involved in the simulation of water flowing through a pipe are the heat loss equation and the pressure loss equation. The simulation of heat loss to the environment uses the following equation [7]:

$$\mathrm{T_{end}} = (T_{start} - T_{env}) \cdot e^{-\frac{(\nabla t \cdot R_\lambda)}{A \cdot \rho \cdot c}} + T_{env} \tag{1}$$

Where T_{start}, T_{env} are the start temperature of the water and the environment in °C or K respectively, ∇t is the time difference between start and end, R_λ is the thermal resistance in W/m · K, A is the cross section area in m^2, ρ is water density and c is water heat capacity.

For pressure loss of mass flow due to friction along the pipe, we used a simplified model from Li et al. [3]: $\nabla p = f \cdot \dot{m}^2$ where ∇p is the pressure loss in pa, f is the friction coefficient in kg^{-1} · m^{-1} and $\dot{m}$ is the mass flow in kg/s.

An important cause of the complexity of modelling a district heat grid is the delay effect of the pipes. We model the dynamics in the edge/pipe using the node method [7]. An illustration of this method is provided in Figure 1.

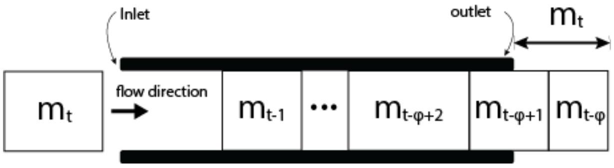

Figure 1: The simulation method of water in an edge. Water comes in at each time step is treated as a block with mass, entry temperature and entry step

In this method, water is treated as if it is a rigid block, called plug. A plug saves the information of mass, entry temperature and entry step. An edge is filled with plugs of which the mass always adds up to the mass that the edge can contain. A plug cannot be compressed and no heat exchange happens between plugs.

When solving the edge, the mass m_t has to be specified prior to the computation from either upstream or downstream. The plugs to be pushed out of/ into the edge are then calculated with the node method. The input, output and the constraint of an Edge are shown in Table 1.

Table 1 The input, output parameters and constraints of an Edge. *Delay matrix is to track, for example, for water flows out at t = 5, 40% are from t = 2 and 60% are from t = 3

Input parameters			
	Diameter	Length	R_λ (thermal resistance)
	c (heat capacity)	ρ (density)	T_{env}
	f (friction coef.)		
Output parameters			
	Inlet/outlet T	Mass flow	Delay matrix*
	Heat loss	Heat in pipe	Pressure loss
Constraints			
	Max flow speed	Min flow speed	

2.3 The Consumer

The relation between the heat the consumer received and the inlet, outlet temperature and mass flow is defined by:

$$\nabla Q = (T_{in} - T_{out}) \cdot \dot{m} \cdot c \quad (2)$$

A consumer always has a built-in heat exchanger (HX), as shown in Figure 2. Each consumer has a fixed inlet temperature at the consumer side of the heat exchanger (so not in the main grid) T'_{in}, and the consumer side outlet temperature T'_{out} is assumed to stay constant unless the demand is not met. Note that this is the model of a heat exchanger that has a control to guarantee a constant temperature at the consumer outlet side. The mass flow $\dot{m}'$is calculated so that the demand is met. Then we calculate T_{out} and $\dot{m}$ of the grid side using the NTU and LMTD methods [8]. When demand cannot be met, NTU is used. Otherwise, LMTD is used as it has better accuracy. Interested readers can refer to our source code for detailed implementation. Finally, the pressure load of the consumer is assumed to be a constant ∇p_c.

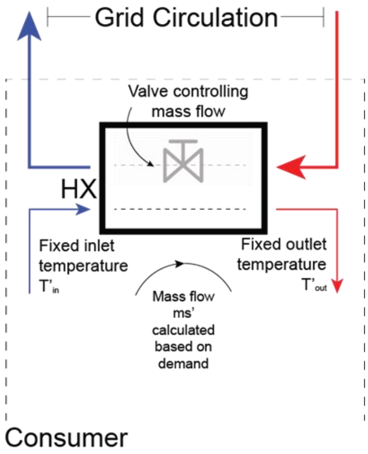

Figure 2: The structure of a consumer with built-in heat exchanger.

The computation of the consumer goes as follows: it retrieves an approximated inlet temperature T_{in} from the upstream component. Alternatively, it can retrieve a list of plugs: (temperature, mass) from the upstream pipe for better accuracy with more computation time and calculate the mass flow of each time during the time step. The current implementation uses the latter way. Then it calculates the average mass flow $\dot{m}$ in this time step and outlet temperature T_{out}. The input, output and constraints on a Consumer are shown in Table 2.

Table 2: The input, output parameters and constraints of a Consumer.

Input parameters			
	Demand	*c* (heat capacity)	$\dot{m}_{max}$
	A (surface area)	q, k(HX parameters)	∇p_c
	$T_{in,min}$	T'_{in}	T'_{out}
Output parameters			
	Inlet/outlet *T*	Mass flow	Delivered heat
Constraints			
	Demand satisfaction		

2.4 Producer (CHP)

A producer adds heat to the grid by consuming fuel or electricity and may produce electricity itself. The water pump is also modelled inside the producer. Currently we only have the Combined Heat and Power Plant (CHP) modelled, but other types can be added easily.

The key to model a CHP is an operating region and the corresponding cost. Most research in this field use a key-point approach or can be represented by a key-point approach [3] [4] [10] and this is what we implemented in GridPenguin. As shown in Figure 3, the user defines a convex operation region by a set of points $(H_1, P_1), (H_2, P_2)$. In addition, a cost array (α, β) must be defined so that the cost:

$$C = \alpha \cdot H + \beta \cdot P \tag{3}$$

where (H, P) is any point inside the operating region [11]. The CHP also has ramping constraints on heat, power and outlet temperature.

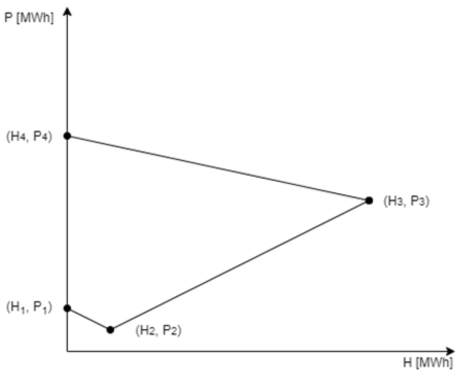

Figure 3: The operation region of the CHP, defined by 4 key points. H: heat production. P: power production.

The CHP can take either outlet temperature or heat production as input, together with power production. The resulting computations are slightly different. When the outlet temperature is the input, the downstream component can get an accurate outlet temperature from the CHP. However, when the input is the heat production, the downstream component does not know what temperature it is getting from the producer. So when it retrieves temperature from the producer, it also needs to provide information about an (approximated) mass flow.

The computation of the CHP itself is simple. If the outlet temperature is given, it calculates the heat production, or the other way around if the heat production is given. Next, it checks if any constraints are violated. Finally, it calculates a margin:

$$F = -\frac{C}{\eta} + \gamma \cdot P \tag{4}$$

where γ is the market electricity price and η is CHP efficiency. The input, output and constraints of a CHP are shown in Table 3.

Table 3: The input, output parameters and constraints of a CHP.

Input parameters			
	T_{out} or H	P (power production)	α, β (cost coef.)
	γ (electricity price)	∇p_c	pump efficiency
	ρ (density)	η (efficiency)	*c* (heat capacity)
Output parameters			
	Inlet/outlet *T*	Cost, profit and margin	Mass flow
	Heat, Power production		
Constraints			
	Heat, power, Temperature ramp	(H,E) inside Operation region	$T_{out} < T_{max}$

2.5 The Connector

The Connector is used to split one edge into two or more edges or to merge two or more edges into one. It is necessary for a non-trivial grid with more than one producer and/or more than one consumer.

In the case of one producer and multiple consumers, there will be no control variable for the Connector as the mass flow on the main edge is calculated by the sum of all splits. Take a connector for example with a producer upstream and 3 consumers downstream. The connector will be added 3 times to the solving list by 3 consumers. Each time when it is getting solved, it checks if all mass flows of the downstream edges are known and only then it adds the upstream edge to the solving list.

In the case of multiple producers, the Connector that merges the producers together must decide how much mass is coming from each producer. As an example, take a connector which has two upstream producers and one downstream edge. The downstream edge will be solved first and the outlet mass flow of the branch will be known. A valve split parameter μ must be set by the user/ the optimizer. For example, if $\mu = (0.4,0.6)$ it means 40% of the mass comes from inlet 1 (producer 1) and 60% comes from inlet 2.

2.6 The Pump and Pressure Calculation

Because of the reasons we mentioned in section 2.1, we largely simplified the computation of pressure load and pressure propagation to have a better computation time and make it easier for users who do not have deep knowledge of hydraulic systems. We also do not care about pressure at any arbitrary point in the grid, but only the pressure load of the pump as only this is directly related to cost. The calculation makes sure that the pressure load, hence pump cost, is usually over-estimated. The over-estimation is preferred over under-estimation because then if it is feasible in the simulation, it should also be feasible in the reality.

We propagate the pressure loss, starting from the consumers, through the grid and end at the producers. The final pump cost is:

$$C_{pmp} = \frac{\nabla p \cdot \dot{m}}{\rho \cdot \eta_{pmp}} \tag{5}$$

where η_{pmp} is the efficiency of the pump and ∇p is the pressure difference at the producer/pump.

3 MODEL VALIDATION

To validate the simulator, we compared it with a more complex model for hydraulic systems: Wanda. It has been widely used in both academic and industrial areas for its accurate simulation. We compared two modules mainly: the edge and the heat exchanger (consumer). The producer module is not compared as Wanda does not include a detailed model of a producer/ CHP. The results show that GridPenguin has good accuracy on modelling the relation and propagation of heat, temperature and mass flow.

3.1 Heat loss

Wanda and GridPenguin measure heat loss in different ways. While GridPenguin uses constant heat capacity which introduces a small error, Wanda introduces an error with their discretization approach. It is difficult to say which approach is better. In this section, we set up a single pipe in both software packages. With designated inlet temperature and mass flow, the outlet temperature directly reflects the heat loss; this is therefore monitored.

The first thing we noticed is that while GridPenguin uses the thermal resistance R_λ as a parameter to model heat loss, Wanda uses the heat transfer coefficient U. We show that with $R_\lambda = \pi \cdot d \cdot U$ where d is pipe diameter, the heat loss calculated from them are nearly the same, with a difference less that 0.01%. To study the differences in changing mass flow and what it means to GridPenguin, some changing mass flow patterns are tested. These changing mass flows are generated using Perlin noise, with 3 different octaves (rate of changing). The inlet temperature remains constant. The deviation of cumulative heat loss between Wanda and GridPenguin is almost negligible, as shown in Table 4.

Table 4: Heat loss difference at different mass flow changing rate

Flow speed changing rate (*$10^{-6} m/s^2$)	Difference (%)
4.95	0.0123
1.21	0.0693
0.46	0.340

3.2 Heat Exchanger

For the heat exchanging process, Wanda uses a single parameter: heat transfer coefficient U to represent the heat exchanger, while GridPenguin uses a more complex process to calculate U that is dependent on the mass flow. If we force the U to be the same, the differences between GridPenguin and Wanda outlet temperatures are smaller than 0.005 °C. Thus, we show that U is the only difference between Wanda and GridPenguin. We consider GridPenguin U to be more accurate as it takes mass flows into consideration.

In the real world, the heat exchanger is controlled with a set of logic modules and this comes with a delay. For example, if there is a sudden drop in the secondary outlet temperature, a PID will only open the valve on the primary side a little at a time, resulting in the secondary outlet temperature slowly recovering to the setpoint value. Wanda models the control like this. However, in GridPenguin, we think such small-scale changes are unnecessary, as in a real grid the control takes only few minutes or even seconds to adjust and this is thus insignificant to the time scale we model. So in GridPenguin the control will immediately react to the changing situation.

4 DISCUSSION AND FUTURE WORK

In this section we list the most relevant problems and improvements that future works can pay attention to: 1. The implementation of more complex storage modules and more producer types: geothermal, heat pump, boiler, etc. These are necessary to optimize grids with renewable energy sources, which of course become increasingly common; 2. A more accurate pressure load, especially at the valve of the HX. Although Benonysson [7] states that pump cost is insignificant, our experiments with the pressure do not fully agree with this statement. It might be interesting to implement a more accurate pressure model and try to see from there if pump cost is indeed insignificant; 3. The ability to handle a complex grid topology. The current implementation does not allow a bypass/ bi-directional pipe. However we know such structures exist in real-world grids; 4. The water physics can be more accurate. Currently we use constant density and heat capacity. However a more accurate model would make them temperature-dependent properties; 5. Studies on the speed and scalability of GridPenguin. How fast can the simulator run with different grid sizes? Does it scale more than linearly? 6. New control strategies of HX.

5 CONCLUSION

In the field of district heating optimization, there is a wide variety of methods being proposed, most of which involve mathematical optimization and model predictive control. However, these methods, when being proposed, are usually only compared with simple grid operation strategies as the result of the lack of a cross-board comparison criterion. To address this problem, we propose GridPenguin. It is a powerful and comprehensive tool to simulate a district heating network in both good accuracy and high speed. We use discrete simulation with large time steps (typically 15-60 minutes) to ensure good speed while the node method and the modeling of a pipe with separate water plugs guarantee the accuracy. Details on small time scale are ignored while the energy balance and average flow/temperature on large time scale are calculated as accurately as possible. We use detailed physical equations for the calculation of heat loss and heat exchange. We also have included a detailed model of a producer. Compared with Wanda, a popular existing simulation tool, we show that GridPenguin has good accuracy and speed.

We present GridPenguin as a cross-board metric to evaluate and compare different optimization methods. Meanwhile, the computational speed allows the user to run a large number of simulation within limited time. This opens the possibility to apply data-driven machine learning methods, such as Reinforcement Learning [8], Tree Search and Deep Learning, in the DHS optimization problem.

6 ACKNOWLEDGEMENTS

We thank Ivo Pothof and Sam van der Zwan from Deltares for their discussion on the differences in simulation results between Wanda and GridPenguin.

7 REFERENCES

[1] L. Giraud, M. Merabet, R. Baviere and M. Vallee, “Optimal control of district heating systems using dynamic simulation and mixed integer linear programming,” in *Linkoping University Electronic Press*, 2017.

[2] R. Baviere and M. Vallee, “Optimal temperature control of large scale district heating networks,” *Energy Procedia,* vol. 149, pp. 69--78, 2018.

[3] Z. Li, W. Wu, M. Shahidehpour, J. Wang and B. Zhang, “Combined heat and power dispatch considering pipeline energy storage of district heating network,” *IEEE Transactions on Sustainable Energy,* vol. 7, pp. 12--22, 2015.

[4] L. Merkert, A. A. Haime and S. Hohmann, “Optimal scheduling of combined heat and power generation units using the thermal inertia of the connected district heating grid as energy storage,” *Energies,* vol. 12, p. 266, 2019.

[5] M. Casisi, S. Costanzo, P. Pinamonti and M. Reini, “Two-level evolutionary multi-objective optimization of a district heating system with distributed cogeneration,” *Energies,* vol. 12, p. 114, 2019.

[6] L. Urbanucci, F. D’Ettorre and D. Testi, “A comprehensive methodology for the integrated optimal sizing and operation of cogeneration systems with thermal energy storage,” *Energies,* vol. 12, p. 875, 2019.

[7] A. Benonysson, Dynamic modelling and operational optimization of district heating systems, 1991.

[8] K. Stepanovic, J. Wu, R. Everhardt and M. de Weerdt, “Unlocking the Flexibility of District Heating Pipeline Energy Storage with Reinforcement Learning,” *Energies,* vol. 15, p. 3290, 2022.

[9] T. Fang and R. Lahdelma, "Optimization of combined heat and power production with heat storage based on sliding time window method," *Applied energy,* vol. 162, pp. 723--732, 2016.

[10] A. Bloess, "Modeling of combined heat and power generation in the context of increasing renewable energy penetration," *Applied Energy,* vol. 267, p. 114727, 2020.

[11] H. V. Larsen, H. Palsson, B. Bohm and H. F. Ravn, "Equivalent models for district heating systems," 1999.

VI. Poster Presentations

COMPARING THE CO_2 EMISSION INTENSITY OF THE STEEL INDUSTRIES IN THE EU AND CHINA RESULTING FROM TOP-DOWN AND BOTTOM-UP APPROACHES

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Abstract: Accounting for a 7% share of global CO_2 emissions, the steel industry is one of the key industrial emitters. Due to this large CO_2 emissions contribution, it is crucial to evaluate the CO_2 emissions intensity of steel for energy system modeling and decision making for greenhouse gas emissions policies. A literature review revealed differences for emission factors of the steel industry in China of 862 kg_{CO_2}/t_{steel} between studies whereas for the EU, differences of only 108 kg_{CO_2}/t_{steel} were found. This corresponds to 39% and 8% deviation, respectively. This study investigates the underlying differences that cause the deviations. The analyzed studies were not directly comparable due to the use of bottom-up or top-down approaches. Comparable CO_2 emission factors for each study were calculated to explain their deviations, which were narrowed down to the following causes: Different system boundaries of the steel industry; sub-process-specific emission factors and their influences in bottom-up studies, as well as cash flows and monetary CO_2 emission factors in the top-down study. This study clearly demonstrates that even seemingly long-resolved issues such as CO_2 emission calculations continue to pose challenges for a successful energy transition.

Keywords: Steel industry; CO_2 emission factors; Specific energy consumption; European Union; China; Top-down; Bottom-up

1 INTRODUCTION

In order to design effective CO_2 emissions-reducing measures, such as CO_2 emission taxes or other CO_2 emission prevention policies and investments, it is vital to have a common agreement regarding the quantity of man-made CO_2emission sources. On a communal and business level, these calculations are typically based on emission factors. For the reliability of these, the development of consistent and transparent emission factors remain a challenge [1, pp. 653-654]. Due to the high contribution of the steel sector, which accounted for 7% of global CO_2 emissions in 2019 [2, p. 37] its emission factors are of particular interest.

A literature review investigated the emission factors that are specific per ton of steel produced in a regional average. The right-hand side of Figure 1-1 [3, p. 6] shows an emission factor for China of 3.1 $\boldsymbol{t_{CO_2}/t_{steel}}$, which is the largest steel producer in the world today [2, p. 12], whereas the emission factor of the EU was found to be 1.2 $\boldsymbol{t_{CO_2}/t_{steel}}$, which has the lowest factor according to the corresponding study for 2010 [3, p. 6]. However, the production route specific results from the literature review of the regional average emissions of the two major steel production routes only ranges from 2.301 t_{CO_2}/t_{steel} [4, p. 1182] for the Blast Furnace Basic Oxygen Furnace (BF–BOF) route to 0.322 t_{CO_2}/t_{steel} [5, p. 47] for the primarily scrap-based Electrical Arc Furnace (EAF) route, which are shown on the left-hand side and in the middle of Figure 1-1..

To explain why the Chinese CO_2 emissions lie outside of the process emission ranges, although the EU emissions are within that range, it is first attempted to adjust the scope of the steel industries investigated in terms of comparable system boundaries. Secondly, process-based emissions ranging beyond the average are investigated as a possible explanation for the observed differences.

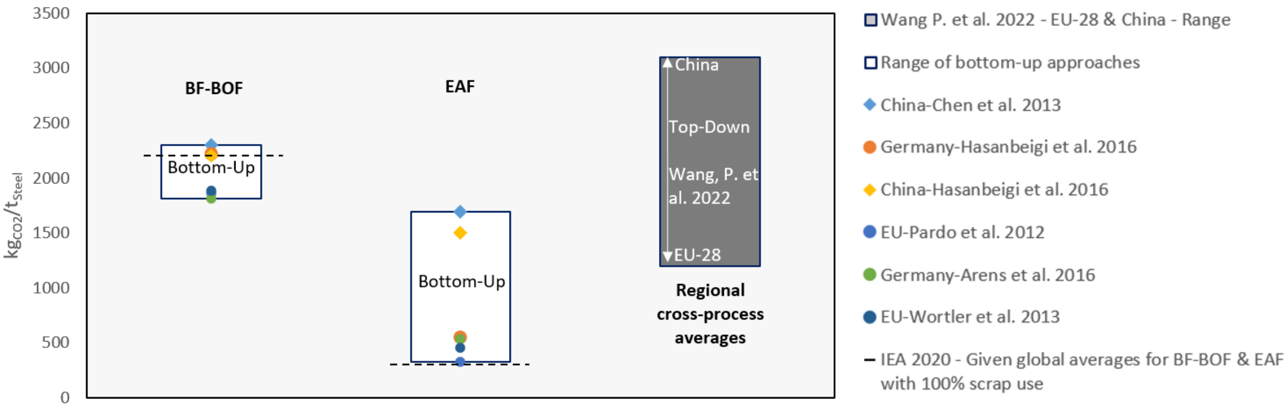

Figure 1-1: Comparison of the specific CO_2 emissions of the EAF and BF-BOF steel production route as well as the regional averages in the EU and China. The graphic is based on data from [2–8]

A challenge for the comparison of the results is the use of top-down and bottom-up models for the regional CO_2 intensities of the steel industry and the process specific CO_2 emission intensities respectively. The process route specific emission factors were determined using so-called bottom-up models [4, p. 1174, 5, p. 7] which analyze the components and interactions between energy sectors from a detailed technical point of view [9, pp. 2-3]. The regional average emission factors [3, p. 6] in Figure 1-1 were determined using a model, that can be classified as a top-down one because it connects the energy system to macro-economic factors [9, pp. 2-3].

2 MATERIALS AND METHODS

The three best documented studies [3–5] from the literature review have been selected so that CO_2 emission intensities calculated by bottom-up and top-down approaches can be compared for the EU and China.

- Wang et al. published a top-down study, that investigated the carbon footprint of the steel industry across 44 countries and agglomerated five rest regions [3, p. 1]. It will be referred to hereinafter as the "Top-Down" study.
- A bottom-up approach was employed to investigate the carbon footprint and energy demand for the Chinese steel industry by Chen et al. [4, p. 1174]. This will be referred to hereinafter as the "Bottom-Up-China" study.

- Another bottom-up approach was taken by Pardo et al. [5, p. 7] to analyze the emissions of the European steel industry. This study will be referred to as the “Bottom-Up-EU” study.

For the comparison of these three studies, the regional average CO_2 emission factor per ton of steel produced across all steel production processes is selected as a compromise of the scopes of the respective steel industry investigated in the studies. Furthermore, the CO_2 emissions per ton of steel specifically for the BF–BOF and EAF routes from both bottom-up studies are compared.

To investigate the comparability of the studies in greater detail, the different scopes and reference years of the steel industry are considered. For temporal comparability, 2010 was chosen as a compromise of data availability for the studies as the base year. Uncertainties and deviations concerning the base year are stated for the respective data. For a clarification of the scope, Figure 2-1 was generated based on the scopes and details considered in the three investigated studies [3–5]. First, the methods of the studies were investigated to determine their comparability. Then, an approach is presented to increase the comparability of the studies and to investigate the influence of CO_2emissions of electricity generationand pig iron input shares towards the emission factor of the EAF. All calculations are provided in excel files in the supplementary provided at: https://doi.org/10.5281/zenodo.6974280 .

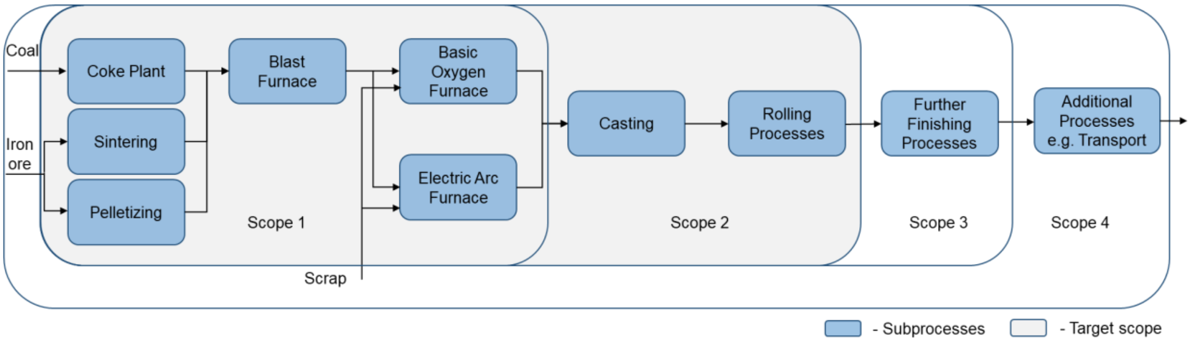

Figure 2-1: (Own depiction) Depiction of the different scopes considered in a steel process or the steel industry. Only scope 4 considers the energy and emissions to produce the input streams.

Top-Down study by Wang et al. [3]

The Top-Down study provided the average emission factor for the EU-28 and China for the years between 2000 and 2015 [3, p. 6]. For this study, they were obtained with some uncertainty due to the graphical extraction. These emission factors include all of the emissions associated with steel production, which corresponds to scope 4 in Figure 2-1. A detailed list of the considered sub-processes is not provided. CO_2 is the only greenhouse gas considered [3, pp. 2-3]. The Top-Down study calculated the t_(CO_2)/t_(steel) in accordance with the procedure presented in Figure 2-2. The total CO_2 emissions were calculated using a method called Environmentally Extended Multi-Regional Input–Output (EE–MRIO) analysis [3, p. 3], which uses the EXIOBASE version 3.4 as input data [3, p. 4].

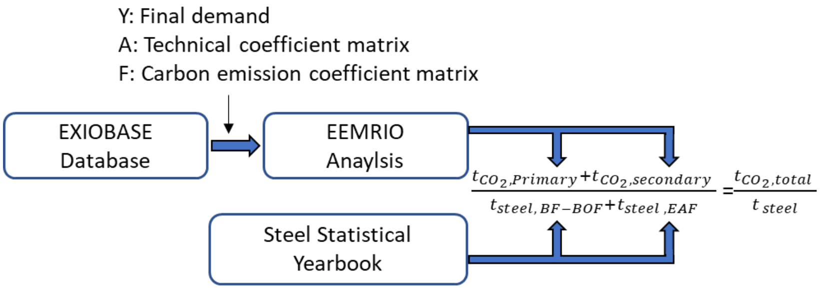

Figure 2 2: Calculation method for the specific carbon dioxide emissions per ton of steel (Own depiction based on [3, pp. 2-4])

The input data provided by EXIOBASE are the technical coefficient matrix A, the final demand Y and the carbon coefficient matrix F for modeling the global economy. F does not have the unit $\mathrm{mass}_{CO_2}/\mathrm{mass}_{\mathrm{steel}}$ and can therefore not be directly compared to the other emission factors of the bottom-up models. Equation 2-1 is a summary of the EEMRIO analysis presented in [10, p. 6] and is used for the calculation of the matrix TC, which contains the CO_2-emissions for all industries in all regions in EXIOBASE. CO_2 emissions from China and the EU can be extracted from the TC. Lastly, regions in EXIOBASE and the steel statistical yearbook are matched by aggregation [3, Supplementary p.3].

$$TC = E * X = F(I - A)^{-1}(I - A)^{-1}Y \qquad (2\text{-}1)$$

Bottom-Up-EU Study by Pardo et al. [5]

In the Bottom-Up-EU study [5], two types of CO_2 emission results, other greenhouse gases are not specifically included or excluded, were used. The first type is an estimated subprocess specific energy consumption and CO_2 emission that is specific to the respective subprocess output stream [5, p. 13]. These correspond to the scope of individual sub-processes presented in Figure 2-1. The second type contains the route-specific energy demand and specific CO_2 emissions [5, pp. 39-40] including the Basic Oxygen Furnace or EAF, which correspond to scope 1. The estimation procedure used for the sub-processes is not further described. Pardo clarified via E-mail [11] that specific energy demand factors are specific per ton of sub-process product. The route-specific CO_2-emissions for the EU were determined in two steps [5, p. 13]:

1. European steel plant emission factors and specific energy demands were determined by agglomerating emission factors and specific energy demands from the subprocesses. The subprocess structure of the plants were obtained from the Plantfactsdatabase [5, p. 21]. In this step, it is assumed that the same sub-process technology has the same CO_2 emission factor [5, p. 21].
2. The steel plant emission factors were calibrated to a collection of steel plant CO_2 emission values, which were reported to the EU commission in accordance with a directive. The anonymized reported data showed that each plant has a unique specific CO_2 emissions profile [5, p. 21]. The following equation (*2-2*) and the parameters described in Table 2-1 [5, p. 22] are used to fit the calculated values to the reported CO_2 emissions.

The Bottom-Up-EU study names 2010 as the base year for the emission data used for calibration [5, p. 22], but the cited EU directive, does not contain the data itself and specifies a timeframe between 2005 and 2010 [12, p. 8] for data collection.

$$CO_{2,p,c} = \left(\frac{Cap_p}{Cap_{ref}}\right)^n * CO_{2,p,o} \qquad (2\text{-}2)$$

Table 2-1: Variables and parameters of the fitting function of the CO_2 emission emission factors of the EUs steel plants [5, p. 22]

Variable/ parameter	$CO_{2,p,c}$	Cap_p	Cap_{ref}	n	$CO_{2,p,o}$
Definition	Calibrated specific CO_2 emissions of the plant	Capacity of the plant	Reference capacity Fitting parameter	Fitting parameter	Original specific CO_2 emissions before the calibration

Bottom-up-China Study by Chen et al. [4]

From the Bottom-Up-China study, the following CO_2 emission results, other greenhouse gases are not specifically included or excluded, were used:

- Sub-process-specific energy consumption that align with scope 2 [4, p. 1178].
- Process route-specific energy demands and specific CO_2 emissions [4, p. 1182].
- Average Chinese steel industry CO_2 emission factors [4, p. 1182].

The Bottom-Up-China study considers the main iron and steel enterprises that produced over 85% of Chinese steel production in 2010 [4, p. 1176]. Sub-processes are further categorized into low-, average- and high-performing enterprises [4, p. 1178]. The data is presented for the years 2005–2010. The 2005 specific energy demands were calculated using a so-called electricity equivalent calculation method [4, p. 1178], whereas the years 2006–2010 were determined using an average fossil efficiency conversion factor [4, p. 1178], without stating further assumptions.

For average-performing steel producers, the specific energy demand for the integrated energy consumption was provided without explicitly stating the included sub-processes. Thus, the value cannot be mapped to a scope in Figure 2-1. Adding up the energy demand provided in [4, p. 1178] for the individual subprocesses of the BF–BOF route does not yield to the energy demand provided in [4, p. 1178] for the integrated BF–BOF route. This indicates that the scope is probably higher than that of scope 2. On the other hand, further steel sub-processes, which would belong to scopes 3 or 4, are not discussed in this study.

For clarification of the scopes, it was attempted to find the six cited sources [4, p. 1176]. These could not be found using a Google, Google Scholar, Web of Science or a Scopus search. A possible explanation is that the source names provided are translations from Chinese. Furthermore, some of the sources are non-persistent URLs, which are no longer reachable. It is not described how the process specific and regional average CO_2 emission factors, which are referred to as the base scenario in the Bottom-Up-China study, were determined for the year 2010.

Approach for study comparison and investigation of the EAF CO_2 emission intensity ranges

For the comparison, it was attempted to convert the three study results into the same scope. Due to a missing detailed list of sub-processes considered in the Top-Down study itself, it was not possible to reduce the scope below 4 which also prevents an increase in the scope of the bottom-up studies. Still, an approach for the conversion of the Bottom-Up-EU study to scope 2 was shown to increase the comparability of both bottom-up studies. Lastly, an analysis case was provided to explain the deviation in EAF route-emissions between the Bottom-Up-EU study and the Chinese one.

Both bottom-up approaches provide the process-specific energy demands based on different subprocess steps. The Bottom-Up-China study provides these as energy demand per ton of steel [4, p. 1178], whereas the Bottom-Up-EU one provides them per ton of product of the respective sub-process [5, p. 13]. To compare the energy demand of both studies, the demands from the Bottom-Up-EU study were converted to be specific per ton of steel. Therefore, conversion factors for the intermediate streams [13, p. 304] from the document "Best Available Techniques (BAT) Reference Document for Iron and Steel Production" which relate to the Bottom-Up-EU study, were used.

The Bottom-Up-EU study provides specific energy demands for four different rolling processes shown in [5, p. 13]. In this study it was assumed that the steel only passes one milling process, which represents the major production route [5, p. 12]. The average specific energy demand and CO_2 emission factors of all 4 milling processes were added to the BF–BOF and EAF route to convert the value from scope 1 to scope 2. The energy demand of casting was neglected because its energy demand is estimated to be only 0,06 GJ per ton of liquid steel [13, p. 383].

In order to investigate the influence of the electricity mix and the share of pig iron contributing to the emissions of an EAF, an EAF base process was generated assuming an average European EAF [13, p. 429]. Table 2-2 presents the process energy demands of the EAF base process, for the provision of nitrogen and oxygen, and the process-related CO_2 emission factors. The influence of the electricity's specific CO_2 emissions is shown in Figure 3- 3.

Table 2-2: EAF base case calculation data.

EAF Inputs	Energy demand	Unit	Source	Emission factors	Unit	Source
Electrical power	2.07	GJ/t_{Steel}	[13, p. 429]	EU 96, GER 128, CH 181	kg_{CO2}/GJ	[14]
N2	4.6	MJ/t_{Steel}	[15, p. 7]	EU 96, GER 128, CH 181	kg_{CO2}/GJ	[14]
O2	37.3	MJ/t_{Steel}	[15, p. 7]	EU 96, GER 128, CH 181	kg_{CO2}/GJ	[14]
Natural gas	0.78	GJ/t_{Steel}	[13, p. 429]	56.0	kg_{CO2}/GJ	[15, p. 4]
Coal	0.45	GJ/t_{Steel}	[13, p. 429]	94.2	kg_{CO2}/GJ	[15, p. 4]
Process-related: Decarburization and electrode burn-off				83.9	kg_{CO2}/t_{Steel}	[15, p. 7]

In order to analyze the influence of pig iron share on the carbon footprint in the EAF route in China, the previously defined-EAF base case with electricity CO_2 emission from the Chinese grid was used. The specific CO_2 emission of an EAF as a function of pig iron share was estimated by the addition of the specific CO_2 emission proportional to the pig iron share in the EAF. Additional energy fed into the EAF by the pig iron was neglected. The specific CO_2 emissions of pig iron were calculated by subtracting the CO_2 emissions of the sub-processes for steel rolling and BOF from the complete BF–BOF [4, p. 1182] route of the Bottom-Up-China study. The specific CO_2 emissions of steel rolling were estimated by multiplying the given specific energy demand of steel rolling [4, p. 1178] with the CO_2 emission factors of Chinese electricity in 2010 [14]. As the Bottom-Up-China study does not provide specific CO_2 emissions for the BOF, the corresponding specific CO_2 emissions of the Bottom-up-EU study [5, p. 13] were used instead. The results are shown on the right side in Figure 3 3.

The total CO_2 emission intensities of the Chinese and the European steel industries were calculated with the process shares for 20Figure 2 310 provided by the statistical steel yearbook [16] and the Bottom-Up-specific route emissions provided by the Bottom-Up-China study [4] and calculated as described above from Bottom-Up-EU study [5], using equation 2-3. The Bottom-Up-China study [4] also provides a total value that closely corresponds to the calculated value from equation 2-3 with a difference of 3 $\mathrm{kg}_{\mathrm{CO}_2}/\mathrm{t}_{steel}$ steel (0.1%). The results are shown in Figure 3 1.

$$Total\left[\frac{kg_{\mathrm{CO}_2}}{t_{Crude\ Steel}}\right] = EAF\ [\%] \times EAF\ \left[\frac{kg_{\mathrm{CO}_2}}{t_{Crude\ Steel}}\right] +\ BFBOF\ [\%] \times BFBOF\left[\frac{kg_{\mathrm{CO}_2}}{t_{Crude\ Steel}}\right] \quad (2\text{-}3)$$

3 RESULTS

This chapter first presents the different CO_2 emission factors of the Top-Down study, Bottom-Up-EU study and the Bottom-Up-China one after adjusting the scopes as much as possible. The reasons for the differences amongst both bottom-up models are shown by comparing the energy requirements of the BF-BOF process and illustrating the dependence of CO_2 emission factors of the EAF process on its feed and the electricity mix of its region. It is shown and then discussed to what extent the differences between the results of the top-down and the bottom-up approaches could be traced as process-based.

Comparison of the average and process specific steel CO_2-emissions

The left-hand side of Figure 5 first shows the specific CO_2 emissions of BF-BOF and EAF routes, followed by the specific CO_2 emissions of the total steel industry using the results from the bottom-up and Top-Down studies in the EU and China. Lastly, the difference between the total CO_2 emissions in the EU and China are shown using the results from the bottom-up studies and from the top-down study, respectively.

Figure 3-1 shows that the EU has less total specific emissions per ton of steel than China independently of the approach used. This is primarily caused by the EAF route's higher share in the EU, which can be seen on the right-hand side of Figure 3-1. Even though the EAF route has higher emissions in China than in the EU, the emissions are still lower than for the BF-BOF route. When comparing the results from the Bottom-Up-EU study and the Top-Down one it can be seen that emissions from the steel industry in the EU only differ by 72 $\mathrm{kg}_{\mathrm{CO}_2}/\mathrm{t}_{steel}$. In contrast to this, there is a twelve-fold larger deviation between the models when comparing the results for China. A comparison between the difference of the emissions in China and the EU shows the difference calculated from the bottom-up results is only 51% of that calculated from the Top-Down study. Underlining the differences between the approaches, the Chinese emission value from the Top-Down study is greater than any of the process routes in the bottom-up studies. A comparison of the bottom-up process routes shows higher specific CO_2 emissions for Chinese BF-BOF steel plants. First an analysis for the differences in the carbon dioxide emissions BF-BOF is presented, followed by an analysis of the EAF emissions.

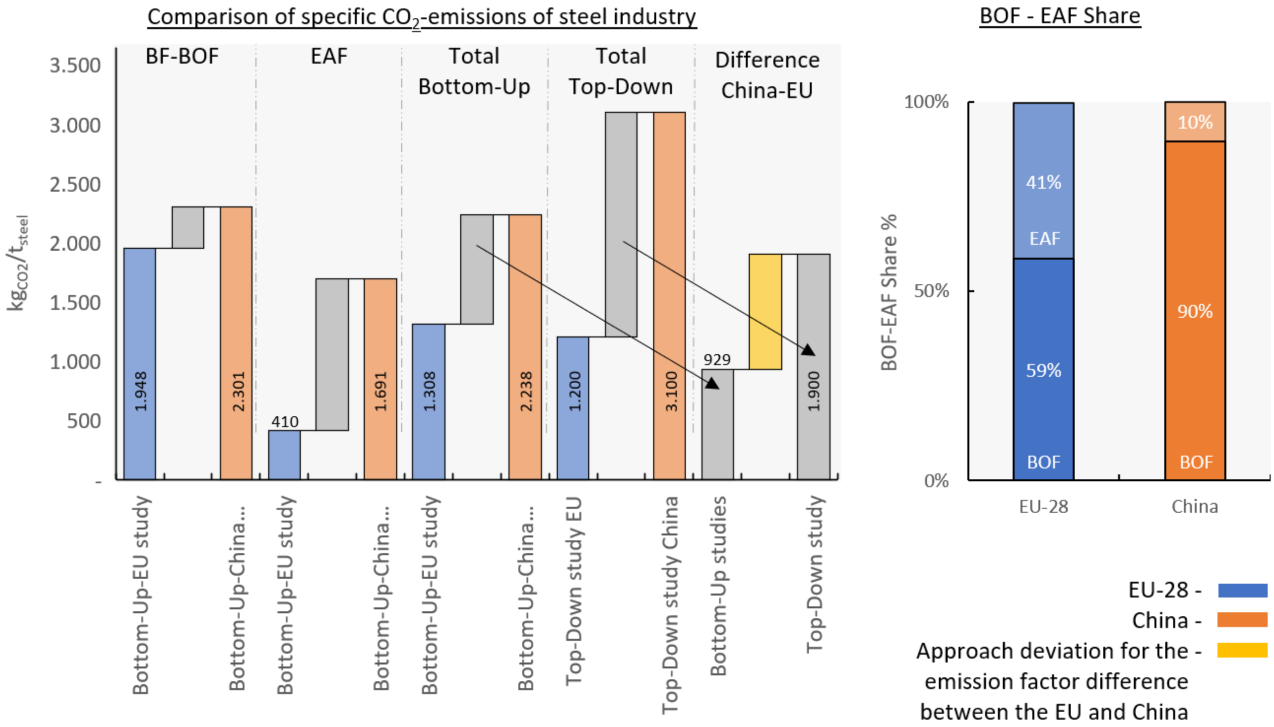

Figure 3-1: Differences between the bottom-up studies [4, 5], between the bottom-up studies and the top-down one [3] partly enabled by own calculations – see section 2 – and the BOF–EAF share in 2010 [16, p. 16]

Bottom-up BF-BOF emissions intensity main influences

The CO_2 emissions can be calculated from energy demand using emission factors. Therefore, the energy demands provide a good insight into the CO_2 intensity influences of the route. Figure 3-2 shows the energy demands of the BF-BOF sub-processes in scope 2. The blue bars represent the average European energy demand, derived as shown in the Methods section section 2 in regard to the Bottom-Up-EU study [5]. The orange bars represent the average Chinese BF-BOF process values according to the Bottom-Up-China study [4] for the reference year 2010. The Bottom-Up-China study does not clearly state if the energy demand to produce input materials to the processes is included. In Figure 3-2 the results from the Bottom-Up-EU study are shown which exclude the energy demands of input materials. The Bottom-Up-China study also provided process values for high- and low- performance steel plants, which are indicated by the error bars in Figure 3-2. At 60%, the blast furnace has the highest energy demand of the sub-processes for the EU and China as well. The differences between the average Chinese and European steel plants are less than 3%, at 11.7 GJ/t_{steel} and 12.0 GJ/t_{steel}, respectively. The preparatory processes of sintering, pelletizing, and coking together require 5.5 GJ/t_{steel} and 4.36 GJ/t_{steel}, which correspond to a difference of 21%. Negative values of the basic oxygen furnace are caused by the production of BOF gas which can be used as a gaseous fuel [5, p. 12].

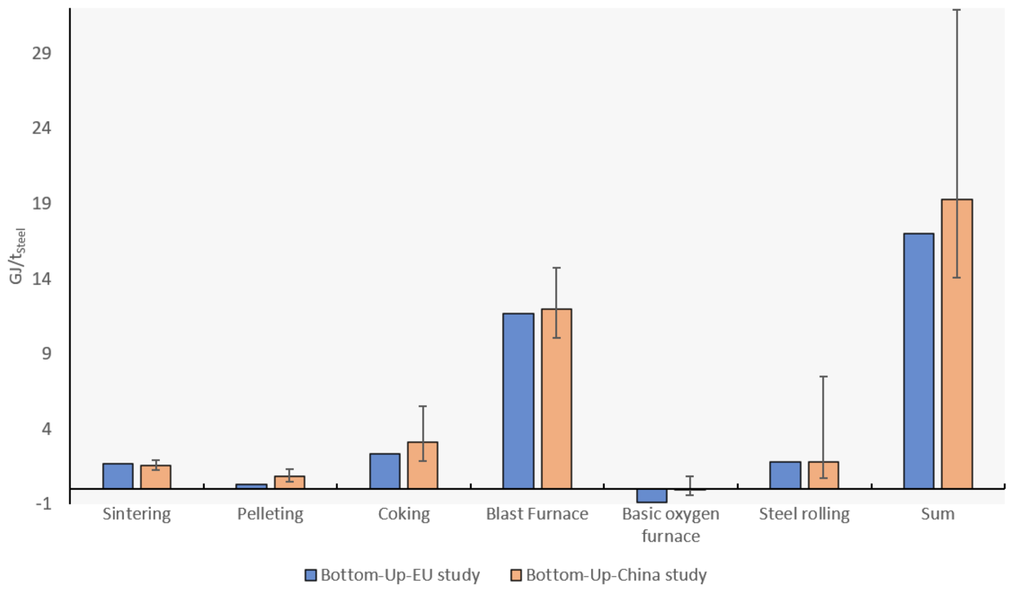

Figure 3-2: Energy demand of process steps of BF-BOF route in China [4, p. 1178] the EU [5, p. 13] . EU values are converted according to the procedure in section using conversion factors from [13, p. 304].

Noteworthy is the large range given by the Bottom-Up-China study [4] to the worst performing steel mill, whose energy demand is almost 80% higher than the average. A large range can also be observed for the first step of the steel rolling, where the worst-performing steel plant uses 7.49 $\mathrm{GJ/t}_{steel}$, which corresponds to almost 40% of the sum of the listed process steps of the Chinese average-performing steel plant. The sum of the process steps considered shows that the worst performing steel plant in China has almost twice the energy demand of an average European steel mill according to the Bottom-Up-EU study [5], whereas the sum of the "best performing" steel plants is below the average energy demand of European steel plants. The sums of the average energy requirements of the process steps differ by 13%, with 19.27 $\mathrm{GJ/t}_{steel}$ and 16.9 $\mathrm{GJ/t}_{steel}$ energy requirements for China and the EU.

Bottom-up EAF Emission Intensity Influences

An estimation of the influences of the electricity mix and the pig iron share towards the $\mathrm{CO_2}$ emissions of an EAF route is shown on the left-hand side and right-hand side of Figure 3-3, respectively. The estimation is based on an average EU–EAF process, which is defined in section 2. The $\mathrm{CO_2}$ emissions do not claim to be reliable absolute emissions but rather maximum emissions due to neglecting the heat introduced into the process by pig iron, for which no data was provided. For all three electricity mixes on the left-hand side, more than 60 % of the specific $\mathrm{CO_2}$-emissions are caused by the electricity demand. The high emission factors for the Chinese EAF route can be explained by the pig iron share which is investigated in the graph on the right.

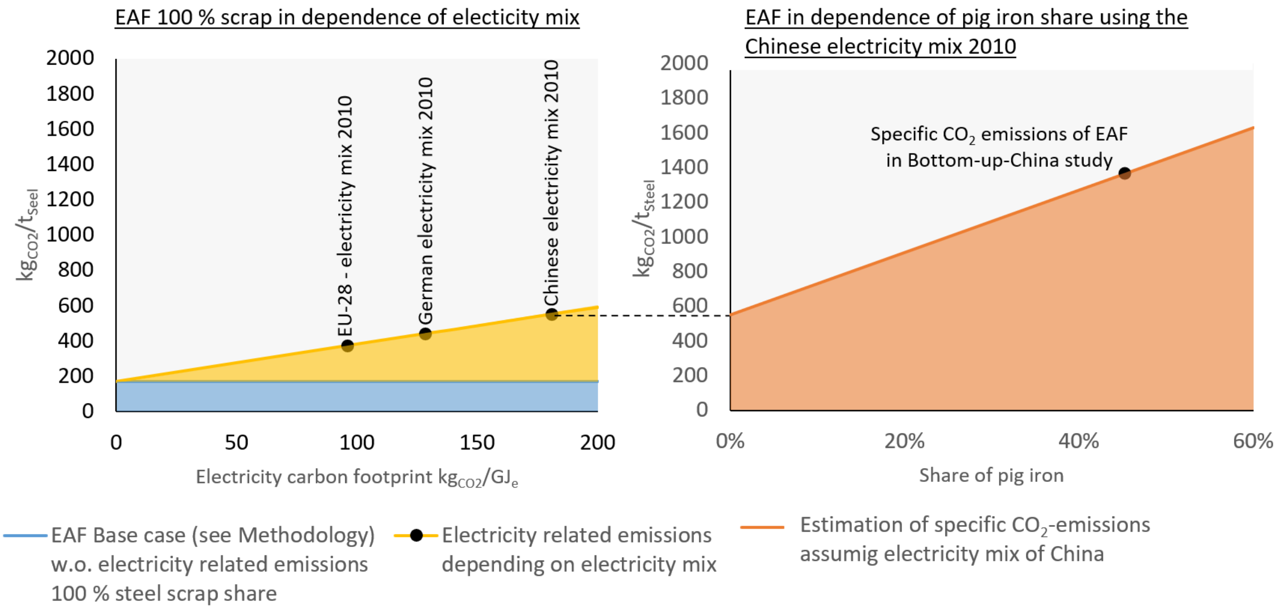

Figure 3-3. Possible combination of the Chinese electricity mix and pig iron share to meet the specific CO₂ emissions of the Bottom-Up-China study's EAF route by own calculations [4, 13–15]

At a pig iron share of 45%, the emissions would match the EAF CO_2 emissions that are provided by the Bottom-Up-China study [4, p. 1182] for Chinas EAF route in 2010, after subtracting the CO_2 emissions of the energy demand for steel rolling, taking into account the Chinese electricity mix in 2010 [14]. With the upper end of usual pig iron input share in China of 60% [17, p. 195], CO_2 emissions would result in 1627.5 kg_{CO_2}/t_{steel} and would therefore not exceed the BF–BOF route carbon emissions. After investigating the emission factor influences of the BF–BOF and the EAF route the high specific CO_2 emissions in the Top-Down study of the Chinese steel industry could be reached, but only if the worst-performing BF–BOF of the Bottom-Up-China study is assumed to be the Chinese average against the study`s specified average

4 DISCUSSION

The three studies are not fully comparable due to deviations in or non-transparent scopes and uncertainties about the reference year. The scopes which are shown in Figure 2-1 of the studies could not be fully aligned for the following reasons:

- The EU emissions had to be converted to scope 2 using estimated specific energy demands and CO_2 emissions for the sub-processes, averaging of milling emissions and uncertainties about the reference year remain as described in section 2.
- The Bottom-Up-China study's average value for CO_2 emissions [4, p. 1182] cannot be precisely mapped to a scope according to Figure 2-1. Still, for the comparisons in Figure 3-1 it is assumed to be in scope 2.
- The Top-Down study includes all CO_2 emissions related to iron and steel production, which corresponds to scope 4 [3, pp. 2-3]. It lacks an explicit list of sub-processes that could be used to align the scopes.

The alignment of scopes has been identified as a general challenge in the determination of emission coefficients by Luers et al. [1, p. 654] and is not only specific to the steel industry.

The generally higher CO_2 emission factors of the whole steel industry in China compared to the EU are primarily caused by the higher ratio of the BF–BOF route to the EAF one in China compared to the EU. As can be seen in Figure 3-1, the EAF route is generally less energy-demanding and less CO_2emission-intensive than the BF–BOF one. Furthermore, the Chinese EAF route is more CO_2-intensive due to the higher share of pig iron as input material. Also, the differences in route-specific emissions are probably caused by a higher emission prevention technology penetration, such as continuous rolling and coke dry quenching.

The disproportional deviation in emission factors differences for the whole steel industry between China and the EU cannot be explained by different assumptions about the share of EAF and BF–BOF routes because both routes have lower emission factors. The EAF route remains less energy intensive than the BF-BOF route when pig iron is used at the upper end of the input range of 60% [17, p. 195] in China. It is unlikely that the difference can only be explained by additional sub-processes considered by a higher scope of the Top-Down study, as the EU emission factors from Top-Down and Bottom-Up study only differ by 8%, or 72 kg_{CO_2}/t_{steel}, whereas the deviation for China is 39%, or 862 kg_{CO_2}/t_{steel}. Still, regional deviations of the CO_2-intensity of sub-processes between scopes 2 and 4 might contribute to the deviation.

The input data used in both approaches could provide an explanation. Figure 3-2 shows that BF–BOF individual steel processes can have a large deviation in energy demand and CO_2 emissions around the average value. This highlights the importance of assumptions regarding the penetration of CO_2 emission prevention technology in the steel industry as the large performance range of the steel rolling process demonstrates. These are implicitly included in the input data of the top-down model namely the gross output X and specific carbon dioxide emissions matrix F. Also, the average emission sub-process specific data for the EU and China implicitly contain data about this penetration. An investigation of the methods used to determine these values could yield a more precise explanation. Transparency about the origin and determination of emission sub-process emissions factors in the bottom-up studies and monetary greenhouse gas emission factors in the top-down study would have been helpful to yield a detailed explanation.

This raises the challenge of obtaining access to the sources used to determine these values and assumptions. Sources of the bottom-up-China study could not be found as described in the method section. The Bottom-Up-EU study cited a directive [5, p. 21] as a source for steel plant facility-level emissions. The directive itself does not contain the data and it is unclear if the data is confidential. The emission factors used in the top-down studies were automatically selected from multiple sources which requires further investigations [18, p. 507].

5 CONCLUSION

The analysis presented in this study provides fundamental insights into the factors influencing regional disparities of CO_2 emission factors of steel production. The deviations and similarities in CO_2 emission factors between the bottom-up and top-down studies investigated could not be fully explained in this study. It is demonstrated that the deviations cannot be fully explained by different or non-transparent scopes of what is considered as steel industry, by uncertainties about the reference year, by steel production route shares, by the electricity mix in the EU and China nor by the pig iron share in the EAF route. A possible explanation is indicated by the high emission factor variance of individual Chinese BF-BOF plants. A shift in the average performance within in the reported performance range in the Bottom-Up-China study could explain the deviation process wise. Further investigation is required to verify or falsify this explanation which requires a higher transparency in the investigated studies. This study clearly highlights that globally reliable and consistent CO_2 emission factor determination remains a challenging field, in which reproducibility is very important

6 REFERENCES

[1] A. Luers, L. Yona, C. B. Field, R. B. Jackson, K. J. Mach, B. W. Cashore, C. Elliott, L. Gifford, C. Honigsberg, L. Klaassen, H. D. Matthews, A. Peng, C. Stoll, M. van Pelt, R. A. Virginia, and L. Joppa, “Make greenhouse-gas accounting reliable - build interoperable systems,” *Nature*, vol. 607, no. 7920, pp. 653–656, 2022, doi: 10.1038/d41586-022-02033-y.

[2] International Energy Agency (IEA), *Iron and Steel Technology Roadmap*: OECD, 2020.

[3] P. Wang, S. Zhao, T. Dai, K. Peng, Q. Zhang, J. Li, and W.-Q. Chen, “Regional disparities in steel production and restrictions to progress on global decarbonization: A cross-national analysis,” *Renewable and Sustainable Energy Reviews*, vol. 161, pp. 1–11, 2022, doi: 10.1016/j.rser.2022.112367.

[4] W. Chen, X. Yin, and D. Ma, “A bottom-up analysis of China’s iron and steel industrial energy consumption and CO2 emissions,” *Applied Energy*, vol. 136, pp. 1174–1183, 2014, doi: 10.1016/j.apenergy.2014.06.002.

[5] N. Pardo, J. A. Moya, and K. Vatopoulos, “Prospective scenarios on energy efficiency and CO2 Emissions in the EU Ion & Steel Industry,” 2012.

[6] Martin Wortler, Felix Schuler, Nicole Voigt, Torben Schmidt, Peter Dahlmann, Hans Bodo Lungen, and Jean-Theo Ghenda, “Steel's Contribution to a Low-Carbon Europe 2050: Technical and Economic Analysis of the Sector's CO2 Abatement Potential,”

[7] A. Hasanbeigi, M. Arens, J. C. R. Cardenas, L. Price, and R. Triolo, “Comparison of carbon dioxide emissions intensity of steel production in China, Germany, Mexico, and the United States,” *Resources, Conservation and Recycling*, vol. 113, pp. 127–139, 2016, doi: 10.1016/j.resconrec.2016.06.008.

[8] M. Arens, E. Worrell, W. Eichhammer, A. Hasanbeigi, and Q. Zhang, “Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany,” *Journal of Cleaner Production*, vol. 163, pp. 84–98, 2016, doi: 10.1016/j.jclepro.2015.12.097.

[9] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, “Classification and challenges of bottom-up energy system models - A review,” *Renewable and Sustainable Energy Reviews*, vol. 129, p. 109917, 2020, doi: 10.1016/j.rser.2020.109917.

[10] K. Stadler, “Pymrio – A Python Based Multi-Regional Input-Output Analysis Toolbox,” *JORS*, vol. 9, no. 1, pp. 1–8, 2021, doi: 10.5334/jors.251.

[11] J. Moya, "Question regarding "Prospective Scenarios on Energy Efficiency and CO2 Emissions in the EU Iron and Steel Industry" - Ares(2022)4983812", E-Mail, Jul. 2022.

[12] P. Office, “Commission Decision of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council (notified under document C(2011) 2772),” [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011D0278&from=ES

[13] Rainer Remus, Miguel A. Aguado-Monsonet. Serge Roudier, Luis Delgado Sancho, *Best Available Techniques (BAT) Reference Document for Iron and Steel Production:*

Industrial emissions Directive 2010/75/EU : integrated pollution prevention and control: Publications Office of the European Union, 2013.

[14] Ember, *Data Explorer | Ember.* [Online]. Available: https://ember-climate.org/data/data-explorer/ (accessed: Jul. 19 2022).

[15] A. Otto, M. Robinius, T. Grube, S. Schiebahn, A. Praktiknjo, and D. Stolten, “Power-to-Steel: Reducing CO2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry,” *Energies*, vol. 10, no. 4, p. 451, 2017, doi: 10.3390/en10040451.

[16] P. L. Norris, “Steel-Statistical-Yearbook-2012,” [Online]. Available: https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2012.pdf

[17] L. Yang, R. Zhu, and G. Ma, “EAF Gas Waste Heat Utilization and Discussion of the Energy Conservation and CO2 Emissions Reduction,” *High Temperature Materials and Processes*, vol. 35, no. 2, pp. 195–200, 2016, doi: 10.1515/htmp-2014-0183.

[18] K. Stadler, R. Wood, T. Bulavskaya, C.-J. Södersten, M. Simas, S. Schmidt, A. Usubiaga, J. Acosta-Fernández, J. Kuenen, M. Bruckner, S. Giljum, S. Lutter, S. Merciai, J. H. Schmidt, M. C. Theurl, C. Plutzar, T. Kastner, N. Eisenmenger, K.-H. Erb, A. de Koning, and A. Tukker, “EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables,” *Journal of Industrial Ecology*, vol. 22, no. 3, pp. 502–515, 2018, doi: 10.1111/jiec.12715.

ENERGY MANAGEMENT AND DIGITALIZATION BIBLIOMETRIC ANALYSIS

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Abstract: In this paper, we want to present an overall structure of the research area, hotspots, of energy management and digitalization. We are applying science mapping methodology which focuses on presenting dynamics among scientific research, visualizing research accumulated over time, and discovering areas of less interest in publications. It includes informetrics, bibliometric analysis, and scientometric analysis. This study relies on Scopus database to collect bibliographic data. This paper identifies journals with the highest number of publications and collaborations between countries. The results show that publications in „Energy management and Digitalization "have an increasing trend. Most studies fall into the Internet of Things, machine learning, and artificial intelligence topics. These last recent years, a small part of the literature has been oriented also in energy management and digitalization with a focus on industry. The majority of the literature is published in the United States, Italy, India, and China.

Keywords: Energy management; Digitalization; Industrial Energy management; Internet of Things; Keyword evolution; Burst analysis; Bibliometric data

1 INTRODUCTION

Energy management has been for a long time intensively studied in academia. Many authors feature different definitions in their research. O'Callaghan et al., defined energy management as monitoring, measuring, recording, analyzing, critically examining, controlling, and redirecting energy and material flow through systems intending to maximize efficiency [1]. Another study relates it to a competitive advantage, energy efficiency, and maximization of profits [2]. Energy management is the strategy of meeting energy demand when and where it is needed [3]. In their research, they define energy management in production as including control, monitoring, and improvement activities for energy efficiency [4]. Energy management is considered a crucial component for the improvement of any organization's energy. Therefore, its role has considerably expanded in the industrial sector. Energy management was viewed as one of the leading functions of industrial management in the 1970s as the result of the rising price of energy and reports about the approaching exhaustion of world energy resources [5].

The objectives of energy management are to minimize energy costs/waste without affecting production and quality and to minimize environmental effects [6]. In these last ten years the evolution of technology has impacted also the energy sector. Digitalization of energy has brought new opportunities to transform the energy landscape. The industry is responsible for around 38% of global final energy consumption and 24% of overall carbon dioxide emissions. Approximately optimization enabled by digitalization could help achieve energy savings of at least 10-20% [7]. In terms of improving energy management, smart grids, microgrids, the Internet of Things (IoT), and blockchain technology's impact on global cities have been discussed. As a result, digital technology can be utilized to help cities manage their energy needs through the implementation of the smart grid. Moreover, blockchain technology provides more secure management of energy data while satisfying energy needs [8]. The scientific research agrees that modern digital technologies such as IoT, Machine learning, artificial intelligence, blockchain, data analytics, and smart grids in the energy sector will lead to innovative solutions for energy use and energy efficiency [9].

2 MATERIALS AND METHODS

In this study, we want to present an overall structure of the research area and hotspots, common points regarding energy management, and digitalization. We are applying science mapping methodology which focuses on presenting dynamics among scientific research, visualizing research accumulated over time, and discovering areas of less interest in publications. It includes informetrics, bibliometric analysis, and scientometric analysis [10], [11]. To implement science mapping we are using the scientometric analysis technique, which has gained wide recognition and is used to analyze trends in the literature. The scientometric analysis is relatively broader than the bibliometric analysis [14]. Overall we are implementing keyword evolution analysis, keyword co-occurrence analysis, keyword citation burst analysis, country co-citation analysis, identifying most published journals, and tracing relevant insights for publications focused on the energy industrial sector. Article keywords are recognized as the best components to reveal literature content, and visualize and evaluate knowledge structure [15]. Researchers have concluded that author keywords can better describe the core concept of the research [16]. We define the keyword evolution, burst analysis, and co-(key)word analysis as complementary to each other and we use all of them to empower our final analysis. Keyword evolution presents the research trends in chronological view, Co-(key)word analysis presents the co-occurrence of the terms identifying potential trends but not in chronological order, and burst analysis defines only typically popular keywords in a specific time frame.

2.1 Data collection

For collecting publications, the following strategy is implemented. Initially papers related to two multidisciplinary themes energy management and digitalization were collected from Scopus database using best representative keywords from literature “industrial energy management”, "energy management", "digitalization", "digitization", "smart factor*", "machine learning", "Internet of Things", "artificial intelligence", "big data", "cyber-physical system", "blockchain", "smart metering" in title-abstract-keywords search. We started using only the energy management keyword at the beginning but as we wanted to have insights from energy management with a focus on industrial production, we added the “industrial energy management” keyword. Moreover, we conducted another search of papers using only "industrial energy management" with the other terms and found that these papers were part of the initial search of papers using the "energy management" keyword. In an advanced search of publication options provided by the Scopus database, we interrelated these two terms “energy management”, and “industrial energy management” using the <OR> logical operator, while the other terms were used <AND> logic operator [17]. We wanted to note that we used the "smart factor*" keyword and not "industry 4.0" as in literature is suggested that smart factory is a key core concept of industry 4.0 [18]–[21]. The literature is limited between 2011 and 2021. The total number of papers retrieved by queries was 2580. In the pre-processing phase of our data, 150 papers had no author keywords and were automatically removed from the database, 391 papers were duplicated and removed from our database. Finally, a total of 2039 papers were included in our database and used for further investigations on analysis. We want to highlight the fact that these keywords and queries are used to construct our database with publications. In the next step, we collect only author keywords from publications and continue our further analysis of keyword evolution and different network analysis from text data.

2.2 Descriptive analysis

Figure 2-1 shows the distribution of publications chronologically in the interval between 2011 and 2021. There is a steady increase tendency in the number of articles published peaked in 2019. This indicates that the linkage between energy management and digitalization is gaining major interest in the last decade. The articles published in 2021 are retrieved in the third quarter of the year, consequentially the total number of publications for this year is not complete.

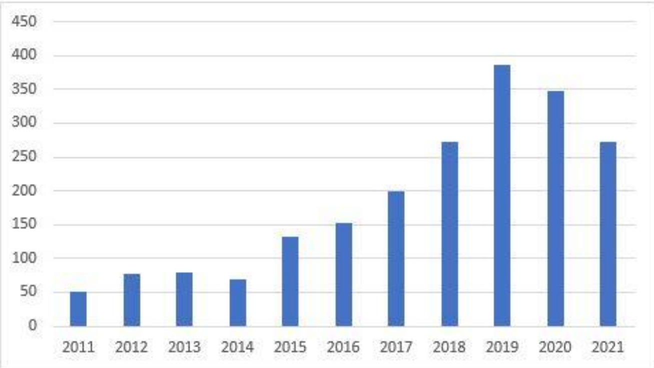


Figure 2-1: Annual publications between 2011 and 2021

Figure 2-2 demonstrates the percentual contribution of each category of publications retrieved from the Scopus database using respective queries. The legend was edited based on the query name. It can be noticed that the majority of publications come from “smart metering”, “machine

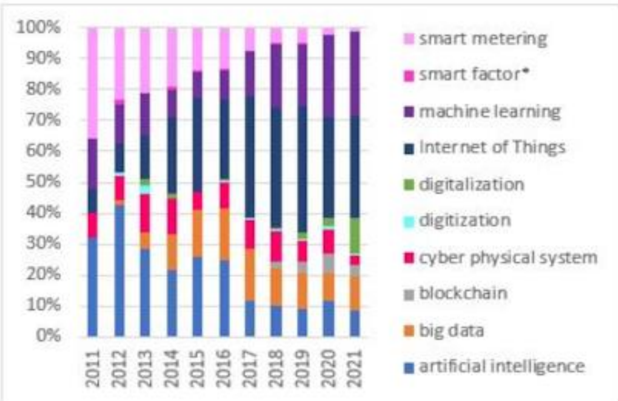


Figure 2-2: Publication distribution based on categories contribution

learning”,” Internet of Things”, “big data”, “artificial intelligence”. The least number of studies derive from “smart factory”, “blockchain”, “digitization”, “digitalization”. It is worth mentioning that smart factories and blockchain technology are considered new paradigms [22], [23].

We were interested to know how many of these publications were focused on the industrial sector. Again, we used keyword frequency analysis. We searched in the title, abstract, and keywords of our database where the terms „industry “, „industrial energy “, and „industrial energy management" could be found. When the number of publications is considerably high, keyword frequency is considered to be one of the best methods for such a purpose [24].

Publications containing our search terms are mostly published in the recent last years. This is an intuition for the increasing development of industrial energy management in these years. However, if we compare industrial and non-industrial based on frequency of the keywords still the number of industrial publications is relatively small. This might be a good suggestion for content screening of publications.

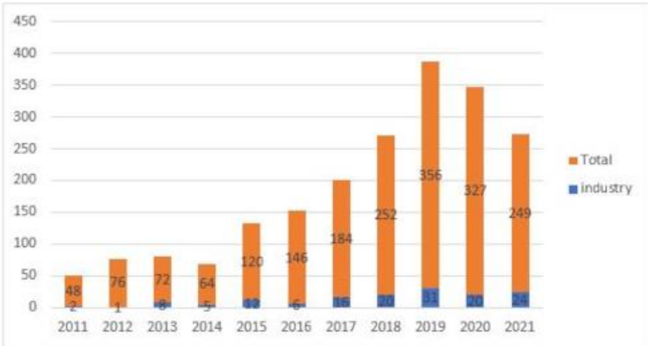


Figure 2-3: "Industry" term related publications

3 RESULTS

3.1 Keyword evolution analysis

After preprocessing the text data (cleaning and filtering stop words) using python, Jupyter notebook we analyzed the twenty most frequent author keywords for each year on our database. Afterward, we found the most common author keywords for the respective years using a threshold of keywords greater than 1 %. For visualization purposes, we decided to group randomly in figure 3-1.

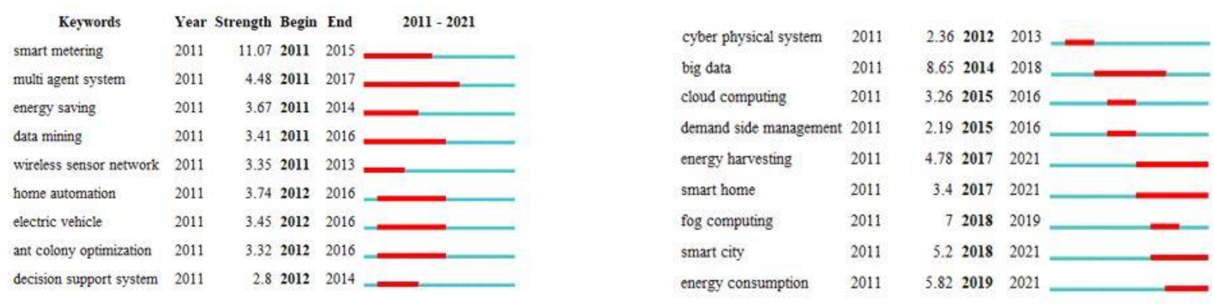
Figure 3-1: Group1, Group2, Group3 keywords

In the first picture, in the first group of keywords, we notice an increasing trend of technology-related research topics such as artificial intelligence, the Internet of Things, big data, and machine learning since 2015. Internet of Things topic results to be the most predominant research topic. Blockchain as already mentioned in previous sections is considered a new emerging technology. As a consequence, the number of publications for blockchain has arisen only since 2018. The second group graph shows the trend of energy-related research topics. The energy management topic increased significantly over the years peaked in 2019.

Demand response, energy efficiency, demand side management, and energy harvesting reflect a similar evolution trend with the exception that energy harvesting started to surge in 2016. Group 3 keyword graph illustrates the evolution of microgrids, smart grid, smart home, and smart metering research topics. Smart grid and smart metering follow a similar trend which gives intuition these keywords must have been used on almost the same publication and might probably refer to the same topic. Smart homes and microgrids have the same trend of fluctuation in peaks and falls.

3.2 Burst analysis

Burst analysis is another analysis we are conducting for a better understanding of the knowledge of our interested multi-discipline energy management and digitalization. This analysis detects keywords that have caught high interest in the publications in explicit periods and provide key research areas [25]. It is based on Kleinberg's algorithm for detecting emerging areas of research. [26]. Burst detection shows rapid changes in frequency, not total frequency [27]. This analysis was conducted using the CiteSpace tool. Data was converted from the RIS file as initially downloaded from the Scopus database to the WoS file, which is the format required from Citespace. During the conversion, only 94 % of the data was successful, in other words, 1962 records. In figure 8 can be seen the results of the analysis (parameter settings: year(s) per slice: 1; node type: Keyword; top N per slice: 20; on burstiness option: gamma 0.5). The red line shows the citation burst for a keyword, while the time interval (between 2011 and 2021) is represented by the blue line, and the strength value shows the weight of used keywords. The higher the value, the more weight the keyword has and is supposed to be relevant for research or gain interest from researchers in that specified period.



Keywords	Year	Strength	Begin	End	2011 - 2021
smart metering	2011	11.07	2011	2015	
multi agent system	2011	4.48	2011	2017	
energy saving	2011	3.67	2011	2014	
data mining	2011	3.41	2011	2016	
wireless sensor network	2011	3.35	2011	2013	
home automation	2011	3.74	2012	2016	
electric vehicle	2011	3.45	2012	2016	
ant colony optimization	2011	3.32	2012	2016	
decision support system	2011	2.8	2012	2014	
cyber physical system	2011	2.36	2012	2013	
big data	2011	8.65	2014	2018	
cloud computing	2011	3.26	2015	2016	
demand side management	2011	2.19	2015	2016	
energy harvesting	2011	4.78	2017	2021	
smart home	2011	3.4	2017	2021	
fog computing	2011	7	2018	2019	
smart city	2011	5.2	2018	2021	
energy consumption	2011	5.82	2019	2021	

Figure3-2: Strongest citation burst keywords

From figure 3-2 can be concluded that on certain keywords there is high research interest. This fact can be noticed from the high value of strength burst. These keywords are „smart metering", „big data", „fog computing", „energy consumption", „smart city", and „energy harvesting". There can be found keywords identified in our first keyword analysis where their frequency was taken into consideration such as „smart metering", „big data", „demand side management", „energy harvesting". This is obvious proof of interest in these areas of research. What is interesting to mention are the keywords that do not appear in our keyword evolution analysis but still have a high value of strength in a certain period such as „fog computing", „smart city", „energy consumption", and „multi agent system". This can certainly indicate a new focus of research, or suggestion for researchers where to focus their research. The last category is these keywords that appear only in burst analysis and have low values of burst strength but still have a considering impact in the field of energy management and digitalization such as „energy saving", „data mining", „wireless sensor network", „home automation", „electric vehicle", „ant colony optimization", „decision support system", „cyber-physical system", „cloud computing". These results might also be a good indication for more focus and research in these areas. Another insight relevant to our analysis is the keywords that have a recent burst implying recent focus research in the year 2021 such as „energy consumption", „smart city", „smart home", and „energy harvesting".

3.3 Co-(key)word analysis

Since keyword frequency can detect research domain interest, a network of keywords will show how research areas are connected. We are implementing keyword co-occurrence network using VOSviewer software, creating a map knowledge based on bibliographic data (parameter settings: type of analysis: co-occurrence; counting method: full counting; unit of analysis: all keywords; minimum number of occurrences of a keyword: A thesaurus file with synonyms was used as common practice in research while working with VOSviewer software. Afterward, the results were used as input for network visualization tool Gephi to identify other metrics beneficial to our analysis.

In figure below nodes represent keywords and edges the relationship between nodes. To validate network results, central measures are used. The degree centrality of a node is a measure

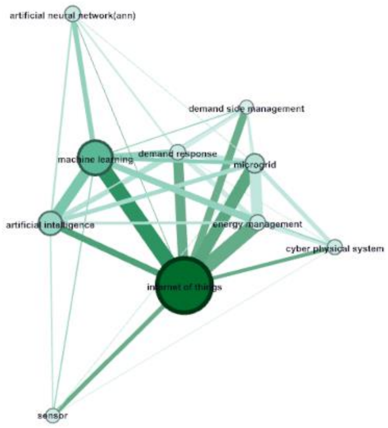


Figure3-3: Keyword co-occurrence network on betweenness centrality filtered by degree

of the number of ties/links that a node has with other nodes within a network. It is used to find strongly connected nodes, popular nodes, which are likely to hold most information [28]. Betweenness centrality measures the number of times a node lies on the shortest path between other nodes. It shows which nodes act as "bridges" between nodes in a network. A high betweenness value of a node indicates that the node holds authority over, or controls collaboration between different clusters in a network or that a node is on the periphery of two clusters [28].

The research focus as already identified in the previous analysis is in „Internet of Things ", „machine learning", „artificial intelligence", „microgrid", „energy management", „demand response", „cyber physical system", „demand side management", „artificial neural network (ann)". In this analysis, we notice that keywords such as „big data" or „blockchain" were not present in the network and did not co-occur with other keywords with the parameter settings we provided of co-occurrence four. Moreover, it is worth noting that the majority of these keywords cannot be found in the burst analysis, confirming that there has been stable continual increasing trend of publications over these research areas and these keywords are considered as coherent terms during the whole interval of time.

3.4 Other analysis

We shortly introduce the journals with the highest number of publications. The top three journals are as follows: IEEE Access, Applied Energy, Advances in Intelligent Systems and Computing, respectively with 72, 57,51 publications.

For the citation analysis of countries, we are setting the following parameters, a minimum number of publications of a country: 25, minimum number of citations of a country (total number of citations these publications have received in the database) :40. We did identify six clusters as follows:

China, Portugal, South Africa first cluster, Pakistan, Saudi Arabia, South Korea second cluster, United States, Italy, India third cluster, France, United Kingdom fourth cluster, Greece, Taiwan fifth cluster and Australia, Turkey last cluster.

3.5 Study limitations

For the keyword evolution analysis, only author keywords were taken into consideration. In the literature review, such a technique is emphasized as reliable and efficient for research and trend detection through keyword frequencies. However, the missing author keywords were filled with controlled terms from keyword plus (indexed keywords) in the Scopus database. Moreover, synonyms or plural forms of the terms were merged during the most common frequent keywords in this analysis, whereas for network analysis in VOS viewer a thesaurus file with synonyms was used. For network analysis during the cleaning and converting process of data, only 94% of our initial data were taken into consideration. To conclude, the consistency in all our analyses is a good indicator for our study.

4 DISCUSSION

Energy management and digitalization have been discussed extensively over this last decade. For such purpose, this study aims to conduct a scientometric analysis analyzing current trends in the literature and providing motivations for future research work in the area. Implemented analyses are descriptive analysis: research growth, top journals, keyword evolution, and secondly, network analysis: co-(key)word analysis and burst analysis.

During our analysis, we notice that publications in „Energy management & Digitalization " have an increasing trend. The articles published in 2021 are retrieved in the third quarter of the year, consequentially the total number of publications for this year is not complete. Moreover, the COVID-19 Crisis might have impacted ´20. Moreover, the majority of studies fall into the Internet of Things, machine learning, and artificial intelligence topics.

These last recent years, a small part of the literature has been oriented also in energy management and digitalization with a focus on industry.

During the inspection of keyword evolution which represents the research theme can be noticed that the most frequent keywords are: energy management, Internet of Things, machine learning, microgrid, smart grid, smart home, smart metering, artificial intelligence, big data, blockchain, demand response, demand side management, energy efficiency, energy harvesting. Many of these keywords have had burst periods i.e., smart metering, big data, demand side management, and energy harvesting. In the burst analysis, can be noticed also other terms with a high value of burst might be considered for further research or investigation.

To identify keyword research topics, co-(key)word analysis has been implemented. The keywords that mostly occur together are Internet of Things, machine learning, energy management, artificial intelligence, microgrid, demand response, cyber physical system, demand side management, and artificial neural network(ann). They imply the main research areas in the literature for our topic of interest. We were also interested to see which were the journals with the highest number of publications. For that purpose, we computed the top five journal analysis where “Advances In Intelligent Systems And Computing”, “IEEE Access”, and “Applied Energy” are the most frequent ones where studies are published. This can be a good point of reference for researchers when they search for literature in “Energy management and digitalization”. Furthermore, can be noticed that the majority of the literature is published in the United States, Italy, India, and China.

5 REFERENCES

[1] P. W. O’Callaghan and S. D. Probert, “Energy management,” *Appl. Energy*, vol. 3, no. 2, pp. 127–138, Apr. 1977, doi: 10.1016/0306-2619(77)90024-1.

[2] R. Kannan and W. Boie, “Energy management practices in SME—case study of a bakery in Germany,” *Energy Convers. Manag.*, vol. 44, no. 6, pp. 945–959, Apr. 2003, doi: 10.1016/S0196-8904(02)00079-1.

[3] E. A. Abdelaziz, R. Saidur, and S. Mekhilef, “A review on energy saving strategies in industrial sector,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 150–168, Jan. 2011, doi: 10.1016/j.rser.2010.09.003.

[4] K. Bunse, M. Vodicka, P. Schönsleben, M. Brülhart, and F. O. Ernst, “Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature,” *J. Clean. Prod.*, vol. 19, no. 6, pp. 667–679, Apr. 2011, doi: 10.1016/j.jclepro.2010.11.011.

[5] G. Petrecca, “Industrial Energy Management: Principles and Applications | SpringerLink.” https://link.springer.com/book/10.1007/978-1-4615-3160-9 (accessed Jul. 25, 2022).

[6] H. J. Loschi *et al.*, “Energy Efficiency in Smart Grid: A Prospective Study on Energy Management Systems,” *Smart Grid Renew. Energy*, vol. 06, no. 08, pp. 250–259, 2015, doi: 10.4236/sgre.2015.68021.

[7] D. P. Verma, D. J. Strüker, M. O. Kjeldsen, and X. Wang, “Digitalization: enabling the new phase of energy efficiency,” p. 16.

[8] S. De Dutta and R. Prasad, “Digitalization of Global Cities and the Smart Grid,” *Wirel. Pers. Commun.*, vol. 113, no. 3, pp. 1385–1395, Aug. 2020, doi: 10.1007/s11277-020-07478-w.

[9] S. Scharl and A. Praktiknjo, “The Role of a Digital Industry 4.0 in a Renewable Energy System,” *Int. J. Energy Res.*, vol. 43, no. 8, pp. 3891–3904, 2019, doi: 10.1002/er.4462.

[10] K. Börner, C. Chen, and K. W. Boyack, “Visualizing knowledge domains,” *Annu. Rev. Inf. Sci. Technol.*, vol. 37, no. 1, pp. 179–255, 2003, doi: 10.1002/aris.1440370106.

[11] S. A. Morris and B. V. der V. Martens, “Mapping research specialties,” *Annu. Rev. Inf. Sci. Technol.*, vol. 42, no. 1, pp. 213–295, 2008, doi: 10.1002/aris.2008.1440420113.

[12] J. L. Heck and W. G. Bremser, “Six Decades of The Accounting Review: A Summary of Author and Institutional Contributors,” *Account. Rev.*, vol. 61, no. 4, pp. 735–744, 1986.

[13] A. PRITCHARD, “Statistical Bibliography or Bibliometrics,” *J. Doc.*, vol. 25, no. 4, pp. 348–349, 1969.

[14] W. W. Hood and C. S. Wilson, “The Literature of Bibliometrics, Scientometrics, and Informetrics,” p. 24, 2001.

[15] H. Su and P.-C. Lee, “Mapping knowledge structure by keyword co-occurrence: A first look at journal papers in Technology Foresight,” *Scientometrics*, vol. 85, pp. 65–79, Oct. 2010, doi: 10.1007/s11192-010-0259-8.

[16] S. Yi and J. Choi, “The organization of scientific knowledge: The structural characteristics of keyword networks,” *Scientometrics*, vol. 90, no. 3, pp. 1015–1026, 2012, doi: 10.1007/s11192-011-0560-1.

[17] “Scopus,” *Wikipedia*. Jul. 22, 2021. Accessed: Jul. 25, 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Scopus&oldid=1034877990

[18] V. Alcácer and V. Cruz-Machado, “Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems,” *Eng. Sci. Technol. Int. J.*, vol. 22, no. 3, pp. 899–919, Jun. 2019, doi: 10.1016/j.jestch.2019.01.006.

[19] B. Motyl, G. Baronio, S. Uberti, D. Speranza, and S. Filippi, “How will Change the Future Engineers’ Skills in the Industry 4.0 Framework? A Questionnaire Survey,” *Procedia Manuf.*, vol. 11, pp. 1501–1509, 2017, doi: 10.1016/j.promfg.2017.07.282.

[20] P. Osterrieder, L. Budde, and T. Friedli, “The smart factory as a key construct of industry 4.0: A systematic literature review,” *Int. J. Prod. Econ.*, vol. 221, p. 107476, Mar. 2020, doi: 10.1016/j.ijpe.2019.08.011.

[21] T. Wagner, C. Herrmann, and S. Thiede, “Industry 4.0 Impacts on Lean Production Systems,” 2017, vol. 63, pp. 125–131. doi: 10.1016/j.procir.2017.02.041.

[22] M. Hoy, “An Introduction to the Blockchain and Its Implications for Libraries and Medicine - PubMed.” https://pubmed.ncbi.nlm.nih.gov/28714815/ (accessed Jul. 25, 2022).

[23] S. A. Puviyarasu and C. da Cunha, “Smart Factory: From concepts to operational sustainable outcomes using test-beds,” *Logforum*, vol. 17, no. 1, pp. 7–23, Mar. 2021, doi: 10.17270/J.LOG.2021.545.

[24] S. Xie, J. Zhang, and Y.-S. Ho, “Assessment of world aerosol research trends by bibliometric analysis,” *Scientometrics*, vol. 77, pp. 113–130, Jan. 2008, doi: 10.1007/s11192-007-1928-0.

[25] Y. Ding, “Scientific collaboration and endorsement: Network analysis of coauthorship and citation networks,” *J. Informetr.*, vol. 5, no. 1, pp. 187–203, Jan. 2011, doi: 10.1016/j.joi.2010.10.008.

[26] C. Chen, “CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature,” *J. Am. Soc. Inf. Sci. Technol.*, vol. 57, no. 3, pp. 359–377, 2006, doi: 10.1002/asi.20317.

[27] M. A. Adabre, A. P. C. Chan, and A. Darko, “A scientometric analysis of the housing affordability literature,” *J. Hous. Built Environ.*, Mar. 2021, doi: 10.1007/s10901-021-09825-0.

[28] K. Cherven, *Mastering Gephi Network Visualization*. Packt Publishing Ltd, 2015.

DIRECT CO_2 ELECTROREDUCTION FROM CEMENT FLUE GAS – OPTIONS AND OPPORTUNITIES

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Abstract: The climate crisis, and the parallel emerging energy crisis, pose an immense challenge to humanity. Central solutions are renewable energy and energy efficiency, to dampen global warming and de-fossilize the concurrent energy supply. Direct carbon capture and electroreduction of CO_2 from cement flue gas addresses both aspects and enables a lean carbon processing directly from flue gas to value-added chemicals. The CO_2 in the flue gas will hereby be captured by an absorber medium, which in addition is used as catholyte in a custom-designed electrolyzer cell; by that, the energy-intense thermal desorption can be eliminated thus reducing the CO_2 footprint efficiently. Central innovation of direct carbon capture and electrolysis is the absorber/catholyte that absorbs and transports large amounts of CO_2 to the electrode for direct use. Here, we elucidate the merits of such process and compare it with the state-of-the-art, further discuss the needs for the electrolyzer cell and the most promising catholyte/absorber media that ensure high performances at maximum cycling stability.

Keywords: CO_2 electrolyzer; Formic acid; Carbon monoxide; Flue gas; Industrial scale; Amine scrubber; Absorber media

1 INTRODUCTION

The cement industry is causing around 7-8% of the worldwide CO_2 emissions [1], mainly through the energy intensive process and the process inherent CO_2 emissions arising from the calcination step. To reach the goal of net zero emissions several roadmaps [2–4] have shown that Carbon Capture and Use/Storage (CCU/CCS) is needed along the way with heat generation by electrification and substitution of raw meal by CO_2 neutral additives. To be more precise around 35% of the CO_2 emission by cement production will be needed to be stored or converted into value-added chemicals (Figure 1).

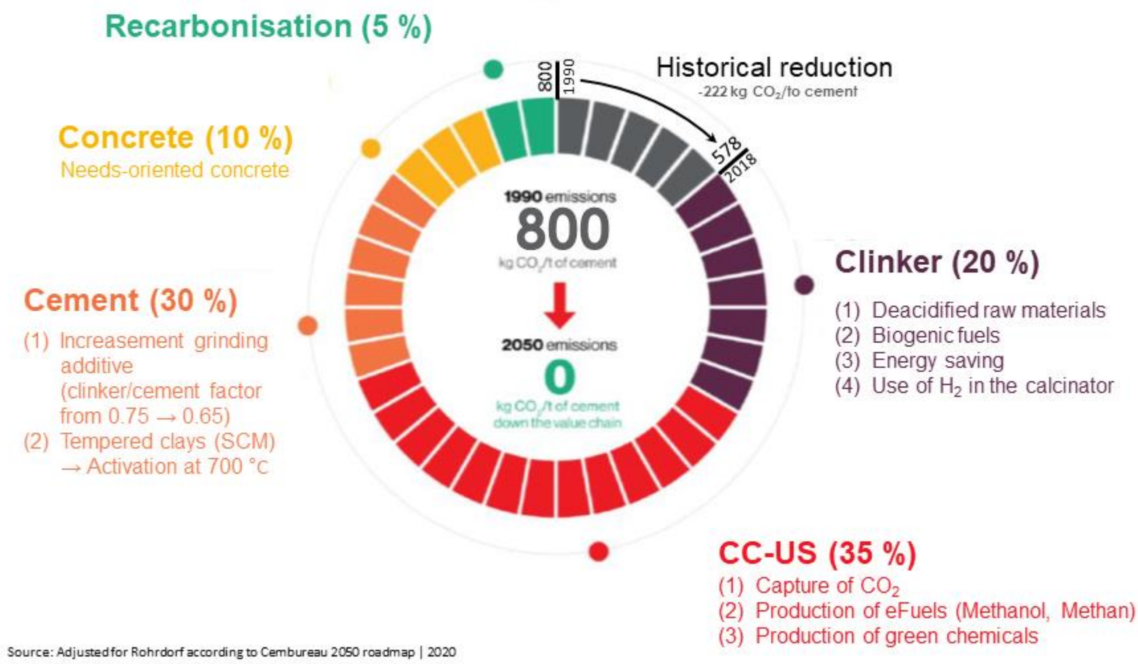

Figure 1: Adjusted roadmap for the reduction of the CO_2 emissions in the Rohrdorfer cement company until 2050. It emphasizes the need for CCUS technologies to reach net zero emissions in the cement sector.

The current level of CCU relies on distinguished solutions:

First, the CO_2 has to be captured and this is dominantly performed via the amine scrubber, a mature technology that captured in industrial scale facilities up to 4.4 Mio tons of CO_2 per year [5]. This amine washers use specially designed solvents that effectively absorb CO_2, while being heat resistant and resisting O_2. The process can capture CO_2 from flue gases (oil, natural gases, coal) with a purity of 99.9%. However, it is an energy intensive process and requires around 4.3 gigajoules (GJ) per ton of CO_2. [6] Furthermore, typical contaminants can be water, O_2 or also degradation products from the amine solvent.

The utilization follows the capture and is predominantly performed through heterogenous hydrogenation such as methanation or methanol synthesis [7]. This process needs a large amount of green hydrogen (CO_2:H_2 = 1:4 (CH_4) or 1:3 (CH_3OH)) additional to pressurized and purified CO_2, which in total is energy intensive and expensive and requires a large infrastructure for H_2 electrolysis and gas storage. The carbon utilization by electrolysis is still under development, but offers in terms of product a more attractive way without the need of H_2, since CO_2 can be converted to e.g. hydrocarbons, alcohols, formic acid or CO. This, however, is still at a technology readiness level (TRL) of 2-3 and is limited currently by a low CO_2 single pass efficiency, as shown by first field-demonstrators [8]. Up to now, the state-of-the-art CCU concepts are based on fractional CO_2 capture and utilization processes and raise severe concerns about their economic and ecologic feasibility, since the capture itself demands 4.3 GJ per ton of CO_2 (desorption and compression in Figure 2) [6]. The direct electroreduction of CO_2 from (cement) flue gas intensifies the process thus reducing complexity, investment and energy consumption via a generic electrolyte/absorber medium that at one hand absorbs large amounts of CO_2 and at the other hand works as electrolyte without disrupting cell and electrocatalyst. Such lean carbon processing potentially raises the carbon efficiency to unity, and thereby decreasing energy demand per ton CO_2 by 30% (Figure 2), as such paving an attractive and feasible power-to-value chain from cement flue gas and related hard-to-abate CO_2-point sources with merit of long-term carbon fixation rates as pivotal step towards a carbon circular economy.

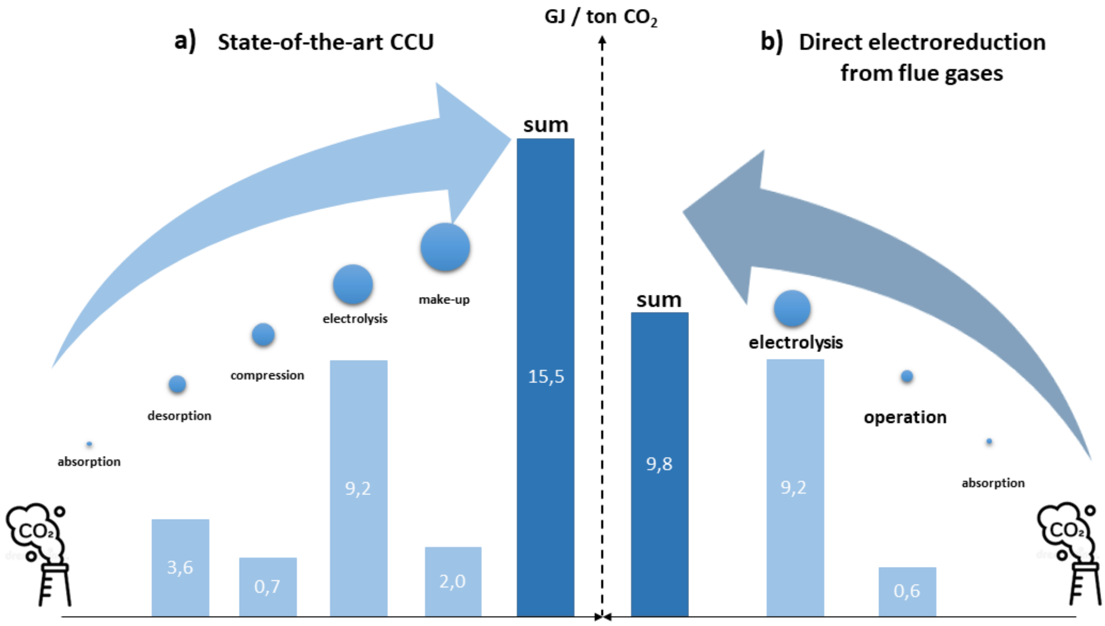

Figure 2: Comparison of the energy demand for state-of-the-art CCU concepts and the direct electroreduction from flue gases. a) Absorption of flue gas, thermal desorption of CO_2, compression and purification, utilization and mandatory make up of (unreacted) CO_2. b) Absorption of flue gas, transfer to the cell and utilization by electrolysis. In both scenarios the energy demand for utilization was depicted for the electrolysis to carbon monoxide. The direct electroreduction decreases the energy demand by a third compared to current state-of-the-art processes.

Here, we shed light in particular at the CO2-to-CO electrolysis [9], potentially also formic acid, both attractive 2-electron reduction products from CO2 levelling the energy demand at 9.2 GJ/ton of CO2. This is low particular to classic hydrogenation products methane and methanol, that afford Fischer-Tropsch kind synthesis with 4 or 3 hydrogen molecules per CO_2 at 36 GJ and 28.5 GJ/ton CO_2. Furthermore, these hydrogenations produce a lot of water and waste heat, which means that a lot of the renewable energy is not used to form the product. However, the CO_2-electrolysis at an industrial scale is still at a low TRL (2-3) and needs further development to become competitive [10]. Here, we show the concepts of our electrolyzer design and the absorber media that drive the direct capture and utilization. Our head-to-tail study points at the potential to reduce energy demand by intensification utilizing CO_2 from flue gases to produce platform chemicals at site.

Materials and Methods: The electrode and reactor design along with the choice of the absorber/electrolyte medium is the most vital part for a successful implementation. There are many possibilities and concepts to design such a reactor [10], e.g., which ion exchange membrane to use, which cell setup and flow geometries, which cathode setup and so on. This mainly depends on the desired product and the choice of the electrolyte and to be economically competitive all electrolyzer compartments have to be mutually optimized. We designed our CO2 electrolyzer based on an already at an industrial scale widely implemented PEM water electrolyzer [11]. Starting from this, the anode compartment was not altered, since it has been improved over the last decade, while the cathode compartment was modified and optimized to

enable the CO2 electroreduction. The extensive fundamental research [12] over the last years enables us to plan CO2 electrolyzer cells at an industrial scale.
The best way to improve and upscale the CO2 electrolyzer is to test it not only at a laboratory scale, but rather start at a point, where the results are meaningful and its easy scalable. Thus, the CO2 electrolyzer cells are built at a different size (Figure 3), to learn from each scale up and to improve the next cell setups.

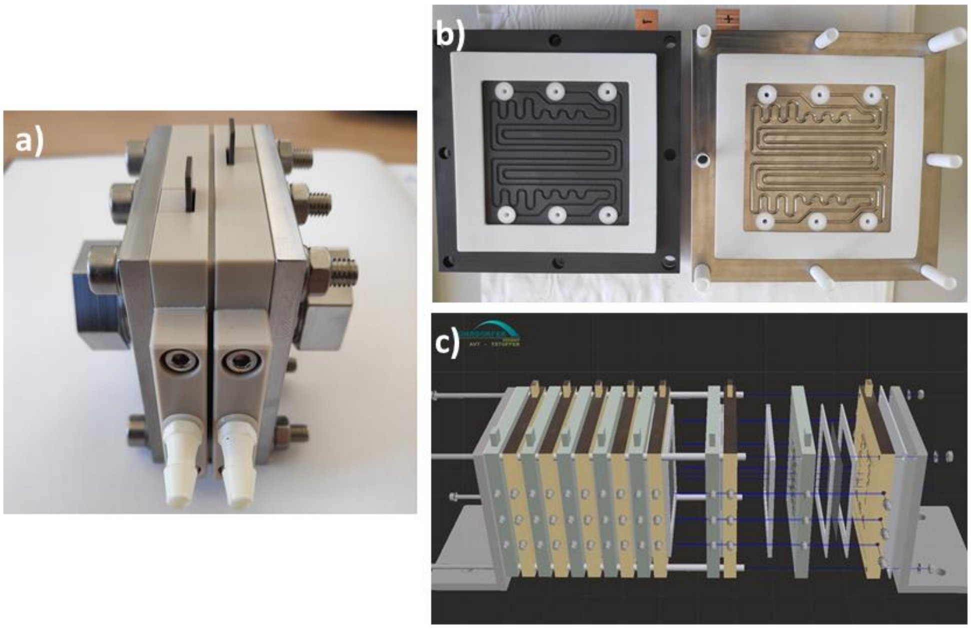

Figure 3: CO_2 electrolyzer cells at a different scale. Electrolyzer cell with a catalyst surface area a) of 4 cm^2 b) of 100 cm^2 and c) of 1000 cm^2.

Furthermore, also the framework conditions such as CO_2 supply and product treatment are of importance for the scale up and hence, we are finishing the planning stage for a demonstrator electrolyzer cell that is able to reduce 1 kg of CO_2/hour.

Apart the overall process, the choice of the absorber medium is the decisive point for a successful implementation of direct electroreduction of CO_2 from flue gas. Here, the medium should exhibit a high CO_2 solubility, degradation and cycling stability, while also having the properties of an electrolyte medium for the cathodic reduction. In this context ionic liquids, organic acids, aqueous ammonia or even amine modifications based on the typical amine scrubber medium are worth considering [13]. Each medium has its advantages and disadvantages and depending on the desired product and the chosen cell design, the best electrolyte medium might differ between different applications.

2 RESULTS

A techno-economic analysis [10] has shown that CO and formic acid are the most attractive products based on the normalized market price ($ per electron). Furthermore, to be economically feasible a Faraday efficiency (FE) of over 90% and current densities over 300 mA/cm^2 should be achieved [10]. The fact that the electroreduction of CO_2 to C_{2+} products does not achieve yet these parameters [10] and the high normalized market price and the low reaction enthalpy (Figure 4) of formic acid (FA) and CO, makes them the best-case products for the CO_2 electroreduction on an industrial scale in the foreseeable future.

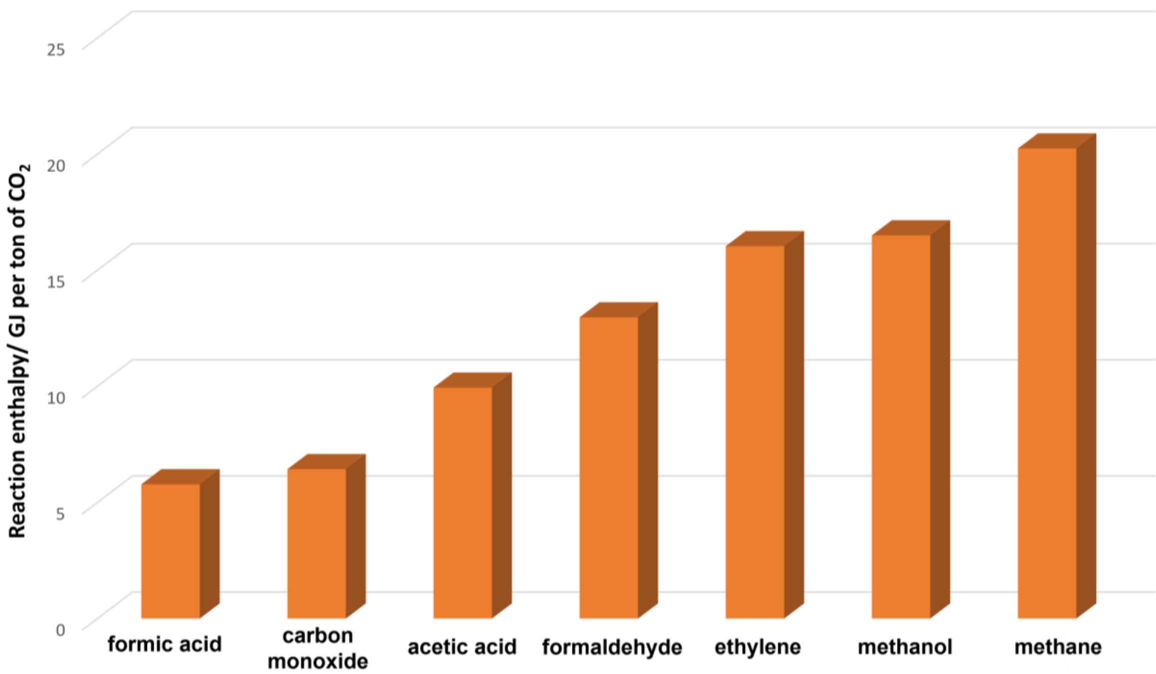

Figure 4: Reaction enthalpy for the formation of several CO_2 electroreduction products. Formic acid and CO show hereby the lowest reaction enthalpy per ton of CO_2.

The CO_2 electrolyzer cells and the corresponding peripheries (educt feed, product release) are hence planned with both options on the table, enabling through slight but distinct modification on the cathode site to either produce FA or CO.

Each CO_2 electrolyzer cell is operated first with a pure CO_2 gas stream to find its best conditions for high current densities, FE and a mature cycling stability. These results and the thereof resulting improvements are simultaneously implemented in all electrolyzer sizes as well as the planning for the demonstrator electrolyzer cell. This should enable the fastest way to an energy- and cost-efficient electroreduction of CO_2 from flue gases on an industrial scale.

To date, first measurements were made with the electrolyzer cell setup of 4 cm^2 and 100 cm^2 (Figure 3 a) and b)), while also finishing the planning for the demonstrator electrolyzer cell, which should be operational within the upcoming months. The demonstrator cell will first pave the way to show the feasibility of such a process and secondly it was planned in a manner that its easily scalable and that the temperature as well as the pressure is variable. More specifically the surroundings are planned for a higher flowrate of the electrolyte, a gas and liquid product separator is planned after the electrolysis (Figure 5) and finally the electrolyzer cells can be stacked into each other (Figure 3c).

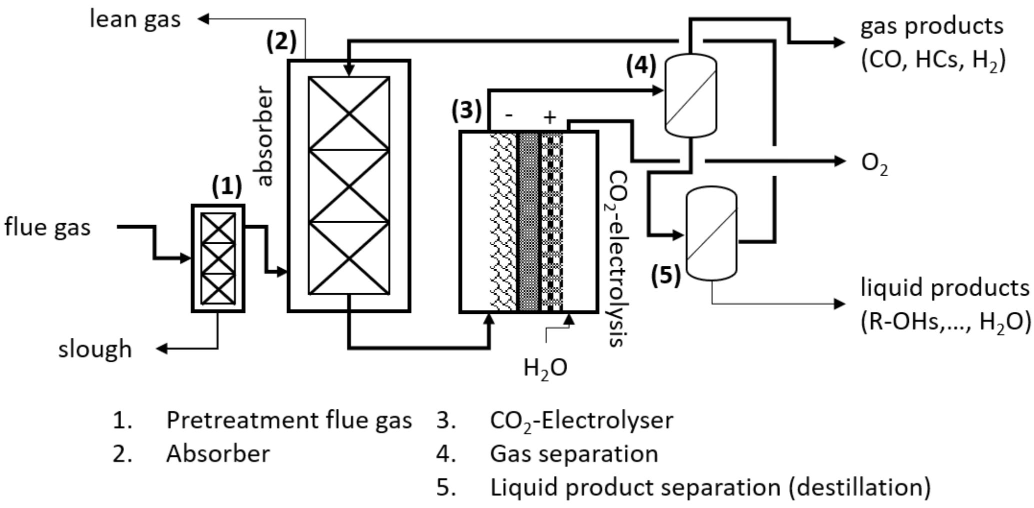

Figure 5: Simplified overview of the direct electroreduction of CO_2 from flue gas. The product separation can either be performed via liquid or gaseous product separation.

However, there are still many uncertainties that need to be addressed and tested. A crucial player with many open questions left is the choice of the electrolyte medium.

Table 1: Comparison of the absorber media for the direct electroreduction of CO_2

Amines or Ammonia	Organic Acids	Ionic Liquids
• High CO_2 solubility • Electrochemical desorption needed – high temperature • Good ionic conductivity • Uncertainties about membrane diffusion and stability • Alkaline pH – high diffusion potential or setup change	• Lowest CO_2 solubility in comparison • Good ionic conductivity • No significant diffusion through the membrane • Membrane stability • Acidic pH – competing H_2 production • Low diffusion potential	• Expensive • High ionic conductivity • High CO_2 solubility • Uncertainties about membrane diffusion and stability • High thermal stability

Here, several important factors such as the stability under flue gas conditions, the separation efficiency, the membrane stability or the diffusion through the membrane are still to be evaluated and an optimum between scalability, costs, electrolyzer performance and energy demand has to be found. In Table 1 the electrolyte media with the most promising features for the direct electroreduction from flue gas are compared and depending on the cell setup the best media might differ.

3 DISCUSSION AND CONCLUSION

The direct electroreduction from cement flue gases can pave the way to net zero CO_2 emissions in the hard-to-abate cement sector. This method could decrease the energy demand by a third through the elimination of the energy intensive desorption step, opening thus a huge potential for an energy- and cost-efficient lean carbon process to value-added commodity chemicals. However, the TRL is low (2-3) and research is needed in this field, especially in the topic of the absorber media and the cell setup. The demonstrator electrolyzer cell will here be an important tool to find the best parameter and conditions for this process, since the whole setup (cell and periphery) can provide results that are pivotal for an industrial scale-up, most favourably, in steps such as laboratory to demonstrator to pilot plant at 1 ton CO_2 per day. The measurements will here first be performed with a pure CO_2 stream to optimize the electrolyzer cell in this regard; in the meantime, the absorber media and the membrane are tested under flue gas conditions to study absorption efficiency, membrane resilience and catalyst stability as well as product diffusion through the membrane. These simultaneous measurements will provide important results regarding the electrochemical cell setup and which absorber medium to use. A successful optimization of these parameters will lead in the next step to a combination of the demonstrator electrolyzer cell with a cement flue gas stream. The proof of concept starts in the upcoming months and is funded by the province of Upper Austria (SKU) and the Austrian Research Promotion Agency (FFG).

4 REFERENCES

[1] R. Pearce, “Q&A: Why cement emissions matter for climate change,” *Carbon Brief*, 13 Sep., 2018. https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change/ (accessed: Jul. 7 2022).
[2] “Roadmap_VOEZ_bis_2050,”
[3] “VDZ-Studie_Dekarbonisierung_von_Zement_und_Beton,”
[4] E. Commission, *ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries,* 1st ed. Luxembourg: Publications Office of the European Union, 2022.
[5] Energy.gov, *Petra Nova - W.A. Parish Project.* [Online]. Available: https://www.energy.gov/fecm/petra-nova-wa-parish-project (accessed: Feb. 15 2022).
[6] P. Luis, “Use of monoethanolamine (MEA) for CO 2 capture in a global scenario: Consequences and alternatives,” *Desalination*, vol. 380, pp. 93–99, 2016, doi: 10.1016/j.desal.2015.08.004.
[7] *Bio-M | BSE Methanol.* [Online]. Available: https://bse-methanol.com/forschung-entwicklung/bio-m/ (accessed: Feb. 16 2022).
[8] CHEMIE TECHNIK, *Power-to-X-Projekt Rheticus startet in Phase 2.* [Online]. Available: https://www.chemietechnik.de/markt/power-to-x-projekt-rheticus-startet-in-phase-2.html (accessed: Feb. 21 2022).
[9] *CO_2 soll saubere Arbeit leisten: Forschungsprojekt Rheticus startet in Phase 2 - Evonik Industries.* [Online]. Available: https://corporate.evonik.de/de/presse/pressemitteilungen/corporate/cosub2-sub-soll-saubere-arbeit-leisten-forschungsprojekt-rheticus-startet-in-phase-2-118327.html (accessed: Feb. 16 2022).

[10] A. Gawel *et al.,* “Electrochemical CO2 reduction - The macroscopic world of electrode design, reactor concepts & economic aspects,” *iScience*, vol. 25, no. 4, p. 104011, 2022, doi: 10.1016/j.isci.2022.104011.

[11] S. Shiva Kumar and V. Himabindu, “Hydrogen production by PEM water electrolysis – A review,” *Materials Science for Energy Technologies*, vol. 2, no. 3, pp. 442–454, 2019, doi: 10.1016/j.mset.2019.03.002.

[12] T. Jaster *et al.,* “Electrochemical CO2 reduction toward multicarbon alcohols - The microscopic world of catalysts & process conditions,” *iScience*, vol. 25, no. 4, p. 104010, 2022, doi: 10.1016/j.isci.2022.104010.

[13] P. Luis, “Use of monoethanolamine (MEA) for CO 2 capture in a global scenario: Consequences and alternatives,” *Desalination*, vol. 380, pp. 93–99, 2016, doi: 10.1016/j.desal.2015.08.004.

NEXT GENERATION THERMAL ENERGY STORAGE FOR INDUSTRY AND BUILDING SECTOR

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Abstract: For realization of the heat transition it is widely accepted that heat for buildings and industry must be 100% RE (Renewable Energy) latest in 2050. The focus of this paper is on heating of buildings via District Grids (DG), but the results are also applicable in industry for T<150°, which is within reach of a 2-stage heat pump and state of the art RE heat sources.

For production of RE and especially Low Temperature (LT) heat the following technologies are commonly used: (A) Heat pumps operated with RE electricity or green gases and (B) Solar Thermal (ST), allowing to heat a collector medium between 80°C (flat collectors) and 400°C (concentrating ST).

In case of buildings the heat demand occurs mostly in 4 winter months, while for industry the time window varies between continuous and shift-wise operation of factories. If we like to utilize ST-heat produced preferably in summer also in winter, seasonal thermal storages are needed.

This paper is about new possibilities to design cost efficient, scalable and large seasonal thermal storages. The cost advantage is realized by replacement of costly ST-collectors (≅300 €/m^2) by a cheap and efficient earth collector, which is part of the storage. In winter, the heat is extracted by means of highly efficient Energy Sheet Piles (ESP).

Possible customers are municipal utilities as DG-operators, or industry, which can use the low-temperature-heat as source for operation of the evaporator circuit of a heat pump. Optimization of the system performance requires prognostic tools for balancing supply and demand [7].

As a first result, a benchmark regarding technology and cost has been performed between state of the art DG-concepts using ST and small storages and the seasonal storage concept.

Keywords: Heat transition, Low temperature heat, Solar thermal collectors, Heat pumps, Seasonal storage, Demand Side Management, Sheet Piles.

1 INTRODUCTION

Solar radiation reaching the earth's surface exceeds with 1.000 kWh/m^2 the energy demand of our planet by a factor of 1.000. However, 80% of the radiation is offshore, and for the remaining 20% the area for harvesting RE via e.g. rooftop PV or ST is limited, especially in cities. This situation is slightly better if PVT-collectors for co-generation of electricity and heat are used /4/.

As shown in Figure 1-1, about 51% of the radiation from the sun is absorbed by and dissipated in the ground, which serves as a “free of cost seasonal storage”. The T-profiles in the ground peak at 13°C on Nov 1st in 4 m depth and at 11,5°C on Feb. 1st in 8 m depth. This is well within the tapping range of Energy Sheet Piles (ESP), as indicated by the yellow bar. Similar to state-of-the-art- geothermal collectors, also ESP capture heat from the surrounding by means of a liquid flowing in the absorber tube fitted to the sheet pile, refer to Figure 3-2. But while the thermal output of state of the art horizontal collectors is between -1…1 °C, for vertical collectors it is between 4…6 °C because the temperature in 15…150 m is nearly constant at 10°C.

This is a striking USP of Energy Sheet Piles, which is the only near-surface geothermal heat source harvesting heat selectively in heat zones with T >10°C. Important to note is the fact that the heat flow from the earth core to the surface is with < 1 kWh/am^2 by a factor of 1.000 lower than the global solar radiation, which is between 1.000 and 1.300 kWh/m^2 in Germany. The reason is the low thermal conductivity of the dry and hot liquid earth core of only 0,07 W/m^2.

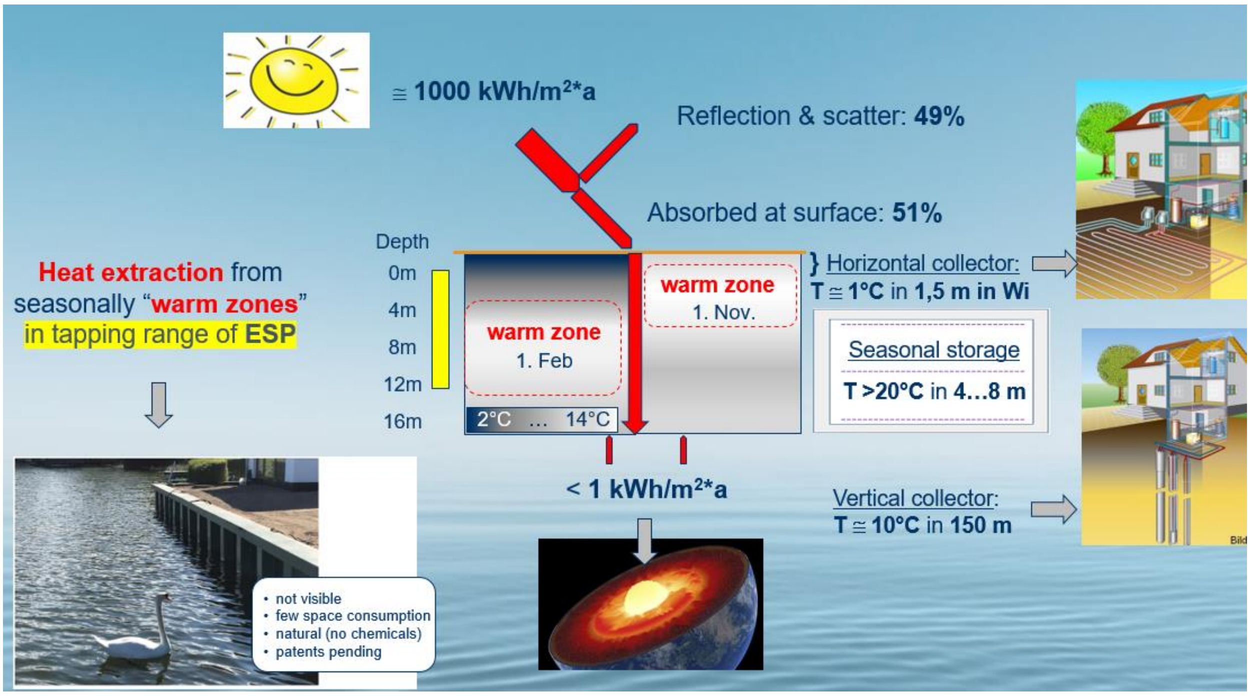


Figure 1-1: Benchmark “Heat harvesting via near-surface geothermal and deep geothermal heat sources”

2 TRENDS IN SOLAR THERMAL FOR DISTRICT GRIDS AND INDUSTRY

The evolution of DGs in shown in Figure 2-1 [6]. The question arises whether DG4.0 - with grid temperatures between 50…60°C - is future proof, or if lowering the temperature down to 30…35°C should be preferred, which is sufficent for area heating systems and allows to minimize the insulation effort of the DG. In this case, houses staying with radiator heaters need additional heat pumps for managing a Temperature-lift according to the demands of the building.

Figure 2-2 shows the energy consumption in Germany 2015 by sectors [3] and the antipicated growth of RE for DGs [1]. According to the left side of Figure 2-2 the grand challenge is to replace

(1) 789 TWh heat in the building sector by RE. Hereof 80% may be realized by heat pumps and 20% by DGs

(2) 543 TWh of industrial process heat by RE and finally to add

(3) 200 TWh RE electric power to the grid for replacing 962 TWh needed in the mobility sector in case of full electrification.

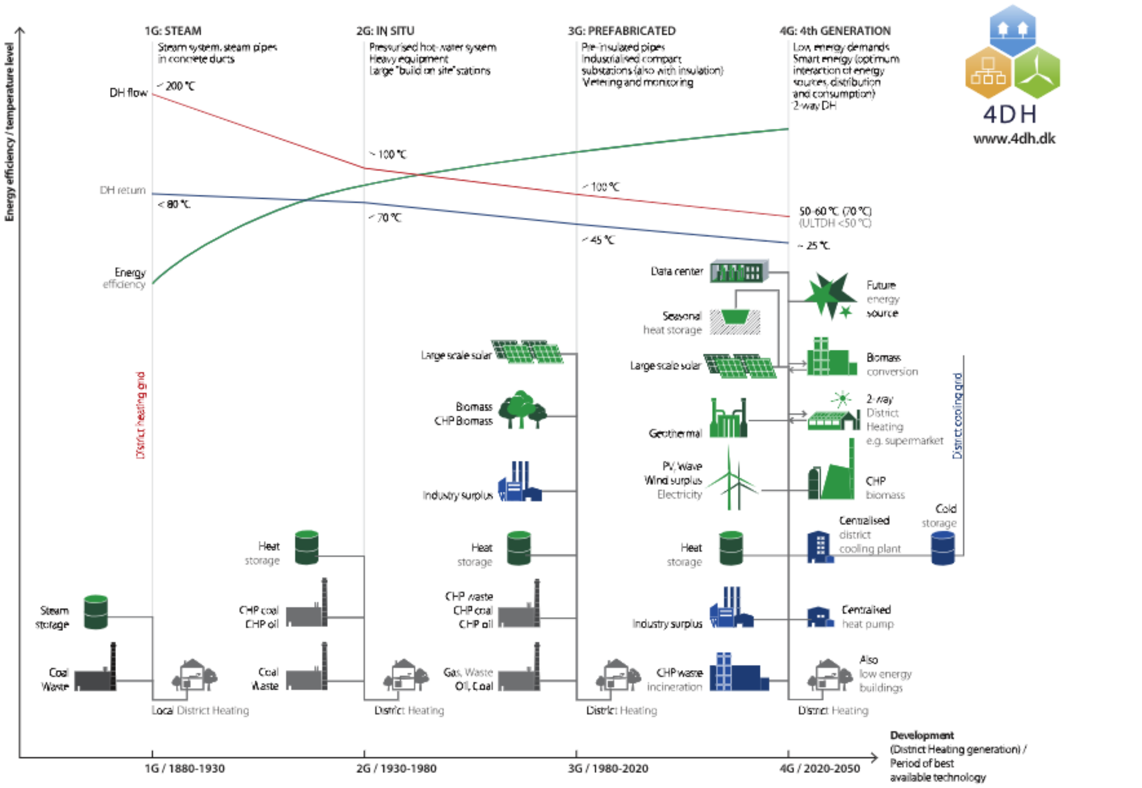


Fig. 1. *From the first to the fourth generation of district heating as published in Ref. [5]. Compared to the first version published in Ref. [1], this version includes Ultra-low temperature DH (ULTDH) and certain other features.*

Figure 2-1: Evolution of District Grids (DG) [6]

An additional challenge for the electric grid are the seasonal fluctuations of the demand side, which will be much higher in winter, when - after replacing oil and gas heaters by heat pumps - another 200 TWh will be needed for operation just of heat pumps. Because PV has no significant RE contribution in winter, the electricity is produced via offshore wind, and this will request additional five 380 kV lines connecting the North Sea with South Germany.

The right side of Figure 2-2 shows the anticipated development of DGs for existing (coal, gas, biomass, …) and future energy sources (electricity & environmental heat and ST). The following trends are visible:

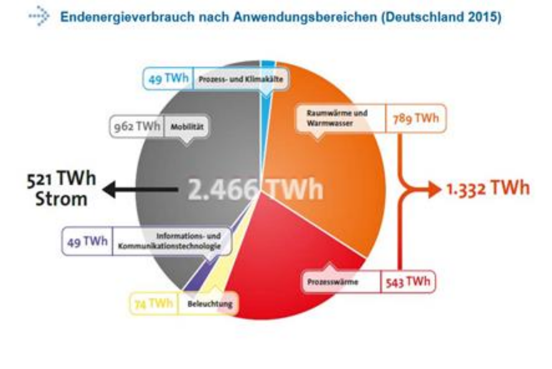
(1) DGs are expected to grow from 145 TWh today to 170 TWh in 2040, from where they start to decline again due to improving building insulation. Today, the share of DG-heat in Germany is about 18% and is expected to increase in the future.

(2) Fossil energies (including gas) will disappear completely between 2040 and 2050.

(3) Strong growth is expected for RE electricity and environmental heat (blue), followed by considerable growth of ST (yellow) and medium growth of geothermal (dark red) and waste heat (light red).

(4) Biomass is expected to decline, probably due to its limited availability.

In case of ST, the question arises how the energy generated in summer can be utilized in winter, which is the topic of the next two chapters.



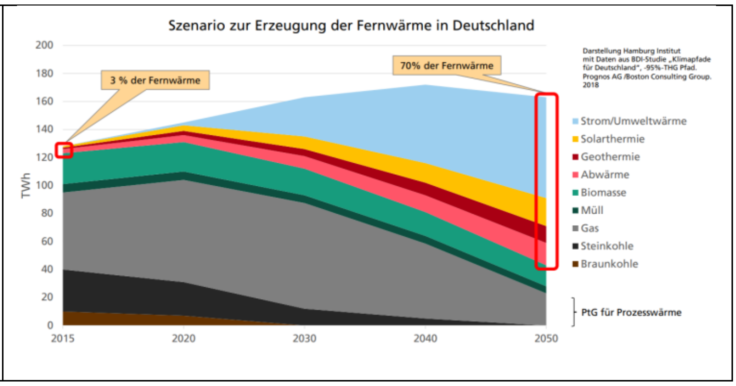


Figure 2-2: Left: Energy consumption in Germany by sectors [3]; right: Growth of DGs by energy sources [1]

3 CONCEPT OF A SEASONAL THERMAL STORAGE FOR LT-HEAT

3.1 Scalable Seasonal Thermal Storage

Figure 3-1 shows a first sketch of a seasonal thermal storage (left part), which is connected to a DG (right part) via a “Grid Station” (middle part). The grid station raises the temperature of the medium coming from the seasonal storage at 15…30°C to 30…35°C via a large heat pump and optionally another non fossil RE source like biomass. The seasonal thermal storage consists of three regions A, B and C:

A. “Inner region”: This region is formed by e.g. state of the art sheet piles (1) w/o thermal activation, which serve for separation from the close-by region B. Region A is humidity controlled for optimization of the loading and unloading phases in summer resp. winter. It also contains (thermally activated) ESP (2) for extraction of the stored heat in winter. In order to minimize radiation losses and losses to ambient air, which are enforced by wind, it is covered at night-time with a foil (not shown I n Fig 3-1), which may be IR-reflecting on the inner side and insulating on the outer side.

B. "Close-by region" (between A and C): In order to keep thermal losses caused by heat conduction into the ground at a reasonable level this region is kept dry by means of a cover (3), which may be e.g. swimming pool liners and the

C. "Uncontrolled outer region", which is slightly heating up due to residual heat conduction through zone B. The losses can be minimized, if the maximum temperature achievable in region A is capped by adjusting the heat capacity of the storage to the heat absorbed in the ground during summer.

The main differences between DG 4.0 as shown in Figure 2-1 are:

- The DG temperature is lowered from 50…60°C to 30…35°C, which is sufficient for area heaters,
- (Non-refurbished) buildings with radiator heaters have an additional heat pump for raising the grid temperature to the (individual) needs of the building and
- The grid consists of consumers and prosumers. While consumers only extract heat from the DG, prosumers do also charge the grid with excess RE heat, produced by e.g. the heat pump or rooftop ST-collectors. This concept is explained in more detail in [7].

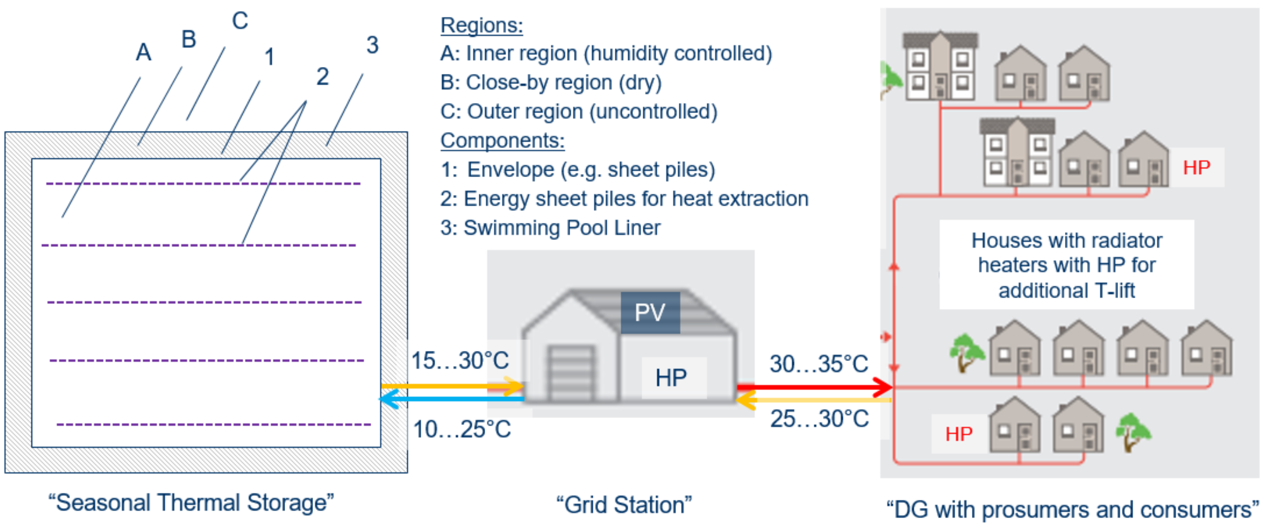


Figure 3-1: Sketch of Seasonal Heat Storage (SS)

Regarding the size of the storage the following estimation can be made: Assuming a heat demand of 20.000 kWh/a per house, a heat capacity of 1,8 kJ/kg for ground @ density of 2.000 kg/m^3, the formula $V=Q/c_p*\Delta T$ leads to a volume of 1.000 m^3 - with ΔT=20°C, which is reasonable to limit the thermal losses by heat conduction through region B. For a village with 1.000 single homes the storage size will be 1 Mio m^3. At a depth of 10 m, which is no problem for sheet piles, the area is 100 ha resp. 14 pitch sizes, which should be manageable for a commune, especially if the area can be used agriculturally.

If the application is an industrial one needing LT-Heat, the temperature output of the Grid Station is higher and adjusted to the needs of the industrial processes. This temperature may be up to 150°C, which can be realized with a 2-stage water-water-HP.

3.2 Energy Sheet Piles (ESP)

For further processing the low temperature heat stored in the seasonal storage a device for extraction of the heat from the ground is needed. This may be done best by means of a thermally activated ESP as shown in Figure 3-2. As indicated in the left figure, the thermal activation of the sheet pile is realized by e.g. connection of U-shaped absorber tubes at one side. The heat extraction power varies from 200…500 W/m^2 for land applications in humid ground to 1.000 W/m^2 at stagnant water as shown on the right side of Figure 3-2 and up to 4.000 W/m^2 at flowing water. This is by a factor of 10 …100 more compared to collector fields with typically 25…30 W/m^2 for humid loam.

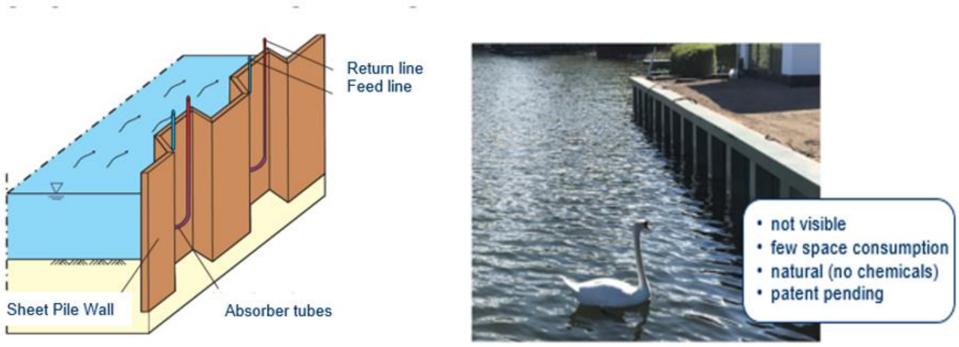


Figure 3-2: Concept of Energy Sheet Piles (ESP);
left: principle /2/; right: Installation at Hotel Deutsches Haus, Feldberg, Germany

3.3 Sector Coupling

Figure 3-3 shows the evolution of electric grids and DGs from the point of view of sector coupling. Starting from the early last century, the electric grid has been fired mainly by coal plants. Adding CHP (Combined Heat and Power) marked the start of DGs (Figure 2-1) with DG temperatures up to 200°C. In the beginning of this century the first PV plants have been added, followed by wind plants. Due to the high volatility of RE and risk of a “Dunkelflaute” redispatch measures are a new challenge for stable grid operation.

Today, all activities for managing the energy transition need sector coupling, meaning that we have - depending on demand and supply - to transform energy from e.g. electricity into heat and vice versa. In this context the message that the “seasonal thermal storage behaves like a virtual electricity storage” gets important, because it (1) makes the heat available harvested and stored during summer, which would be lost otherwise and (2) lowers the electricity demand in winter due to the higher efficiency of the heat pump.

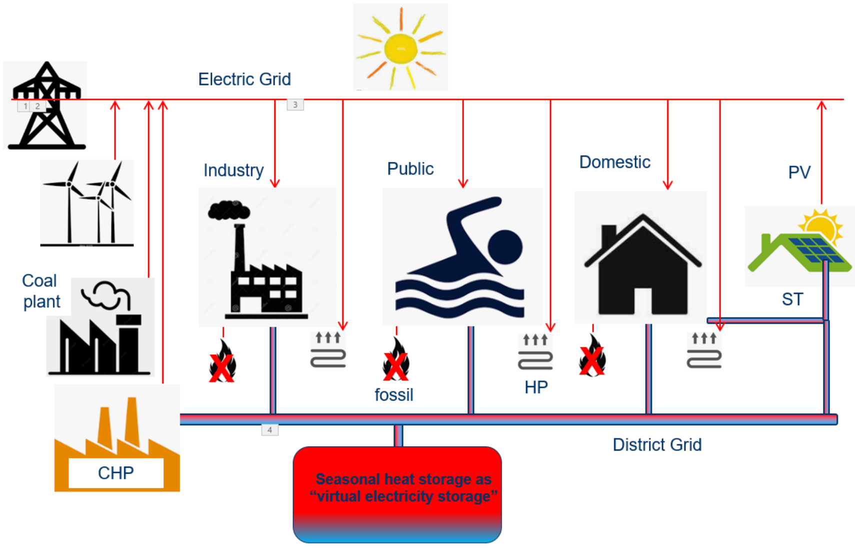


Figure 3-3: Importance of Sector Coupling and effect of seasonal storage

4 BENCHMARK

The concept shown in Figure 3-1 is benchmarked with a concept actually promoted by the Bundesverband für Solarwirtschaft BSW. Here, state of the art ST-collectors of different kind are used along with "small" storages and additional heaters for operation of a DG4.0 as shown on the right side of Figure 2-1. The result for the presented five examples is summarized in table 4-1. Example #6 is based on the proposal of this paper. The benchmark results are shown in table 4-2 for technical aspects and in table 4-3 for economic aspects and are summarized as follows:

- The ST contribution in the BSW examples is between 2% (Lemgo) and 16% (Ettenheim), far from the goal of 100%, which is possible in example #6. This is attributed to the big seasonal gap between supply and demand, which cannot be compensated even with storages in the range of several 1.000 m^3.
- For bridging the gap between demand and supply of ST-heat, a storage size of about 1.000 m^3 is needed per household, meaning that for supply of a village with 1.000 households a storage of 1.000.000 m^3 are needed, which can be reduced e.g. if the assumed 20.000 kWh heating demand is reduced by e.g. insulation measures.
- The BSW request for funding of such concepts should be scrutinized regarding the impact in terms of CO_2 saving in tons per funded € compared to this approach.

#	Ort	Betreiber	Kollektortyp	Speicher/m³	drucklos	Kollektor Fläche/m²	Kollektorleistung/MW	Aufstellfläche/m²	Ertrag/GWh/a	spez. Kollektorleistung/ kWh/m²	CO2-Einsparung/t	Zusatzheizung	dto. Leistung/GWh	Netztemperatur/°C	%RE	Entfernung/km	Wohneinheiten	Wohneinheiten 100% versorgt
1	Ettenheim	Fernwärme Ettenheim GmbH	Flachkollektor	200	nein	1.788		4.200	0,86	478	238	Hackschnitzel, öl	5,3	85/60	16,1%	4	246	53
2	Senftenberg	Stadtwerke Senftenberg	CPC	10	nein	8.300	5,0	20.000	4,2	506	1.064	Gas, Braunkohlestaub	100,0	85/65	4,2%	33	6.250	238
3	Horb	Stadtwerke Horb	VRC	3.000	ja	2.416	1,5	3.243	1,2	?	349	Holz, Hackschnitzel	15,0	85/60	8,0%	7,9	938	78
4	Lemgo	Stadtwerge Lemgo GmbH	VRC	./.	./.	9.118	5,4	17.000	3,3	?	924	KWK Erdgas	155,0	90/65	2,1%	83	9.688	206
5	Ludwigsburg	Stadtwerke Ludwigsburg	Flachkollektor	2.053	nein	14.808	10,4	25.000	5,9	392	1.624	Biomasse, Hackschnitzel	76,9	70/50	7,7%	29,2	4.803	363
6	???	???	Erdreich	500.000	ja	62.500	50.625	55.688	10,0	900	5.558	Wärmepumpe	1,39	30/50	720,0%	???	700	700

Table 4-1: Benchmark of State of the art ST assisted DGs (#1…#5) with seasonal storage (#6)

Topic	BSW Concept #5	SS Concept #6
Area consumption	**14.800 m² flat collector** (10,4 MW) @ **25.000 m² footprint**	**62.500m² (usable for agriculture)**
Visibility	Yes (collector field)	No
Storage size	**2.053 m³** (pressurized)	**500.000 m³** SS
# KfW100 houses	Max 4.800 hh (363 @ 100% served)	556 hh (100% served)
Solar heat	**15 GWh/a** @ 1000 kW/am²	**56 GWh/a** @ 1000 kW/am²
Solar harvesting	**5,8 GWh/a** @ 392 kWh/am²	**28 GWh/a** @ 500 kWh/am² (@ 50% losses)
Auxiliary heating	Biomass, wood (76,9 GWh/a)	Water-Water HP with COP > 10
DG temperature	**50/70°C -> insulation needed**	**30/35°C -> no insulation needed**

Table 4-2: Technical Related Benchmark Results

Topic	BSW Concept #5	SS Concept #6
ST-Collectors	About **4,4 Mio €** for 14.800 m² flat collectors @ 300 €/m² plus 60.000 € for ground (2…3 ha)	About **260.000** for ground (10 ha for SS an DG station) plus cost for sheet piles and accessories
DG-station	Auxiliary heating via gas, biomass, wood etc.	Large heat pump, operated with 100% RE electricity
CO_2-price	**760.000 €/a** in case of gas heating @ 40 €/t CO_2	**Not applicable**
Grid temperature	50…90°C -> **Insulation needed**	30°C -> **w/o insulation possible**
RE-share	**2…16%** -> Auxiliary heating needed	**100%** (in case of 100% RE electricity)
HP for buildings	**Not needed**	**Needed** (houses with radiator heating)
Cost of heat	Goal: < 10 Cts/kWh @ production cost of **5 Cts in 10a**	tbd (Goal: < 8 Cts/kWh)

Table 4-3: Cost Related Benchmark Results

5 SUMMARY AND OUTLOOK

The DG concept with seasonal storage shows some striking advantages over present concepts (with only small storages) regarding performance and cost. From a physical point of view the only serious failure risk is seen in not manageable heat losses from the storage to the air and neighbouring ground, which shall e.g. not be in touch with ground water. The next steps are therefore straightforward:

(1) To start a project with the goal to understand and minimize heat losses in earth storages and

(2) To setup a demonstrator for e.g. a living quarter with a planned LowExDG. Companies planning such a DG are invited for collaboration.

A similar concept of a small seasonal thermal storage for renovation of the building stock is presently investigated in the project HPPVT funded by PTJ, Germany.

6 ABBREVIATIONS AND REFERENCES

6.1 Abbreviations

Shortcut	Meaning	Shortcut	Meaning
CHP	Combined Heat and Power	PV	Photo Voltaic
DG	District Grid	PVT	Photo Voltaic and Thermal
ESP	Energy Sheet Pile	RE	Renewable Energy
HP	Heat Pump	ST	Solar Thermal
LLTTS	Large Low Temperature Thermal Storage	USP	Unique Selling Point
LT	Low Temperature (heat)		

Table 6.1: Abbreviations used in this document

6.2 References

[1] Köhler, B., Sandrock, M., Bürger, V.: „Risiken und Defizite der Wärmewende“, Berliner Energietage 2020

[2] Koppmann, D.: „Energiespundwände - Erschließung regenerativer Energie mittels thermisch aktivierten Stahlspundwänden“, 69. Deutsche Brunnenbauertage 2018

[3] Lücke, A.: “Sektorkopplung und Digitalisierung: Technologietrends im Wärmemarkt”, Berliner Energietage 2017

[4] Noll, T.: “Heating and Cooling for the day after tomorrow”, CISBAT, Lausanne 2019

[5] Noll, T., Puttke, B.: ”Next Generation Energy Sheet Piles and Hybrid Hydro-Power Plants”, Eurosun Athen 2020

[6] Pedersen S.V., 2017. Annex 47: Heat Pumps in District Heating Systems”, EU Heat Pump Summit, Nuremberg 2017

[7] Puttke, B.: “Demand Side Control for LowExDG with seasonal storage”, 2nd NEFI Conference, Linz 2022

HEAT EXCHANGE IN INDUSTRIAL MICROGRIDS

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Abstract: Aim of this paper is the presentation of a new implementation (March 2022) based on a new methodology to increase the energy efficiency by exchanging thermal energy between two buildings. This new methodology comprises several procedures. Firstly, all energy processes involved will be identified, classified, and modelled. Secondly, based on a graphical definition of energy flows, a hydraulic system can be software-independently defined. The solution can be directly exported into a control software programmed with the tool GML (Graphic Motion Language) was chosen. This language allows the creation of SPS programme of the processes defined by PPR (Product Process-model Resources-model).

Keywords: Thermal energy exchange; Energy efficiency; Industry decarbonisation, control software

1 INTRODUCTION

To achieve the goals of the objectives of the Paris Agreement [1], energy exchange in all its ways is a well proofed form of increasing the energy efficiency. Thermal exchange in industry plays an essential role in those contexts [2], where energy overflows can be integrated into different infrastructures or coupled with other industrial activities. Several EU projects have demonstrated the potential of energy saving by heat and cold exchange [3].

In this paper, we present a case of thermal exchange between two buildings of the company STIWA located in Gampern. In the next section we describe the challenges to be achieved and the design of the heating and cooling systems of both buildings based on a hydraulic system. Thereafter, we outline the control model with help of an example to analyze the possible operation modes. The last two sections of the paper cover the description of the control software and a summary of measurements and an outlook.

2 METHODS

2.1 Use case Gampern

The company STIWA has developed a solution for one of its production sites located in Gampern/Austria. The main novelty of this development is the implementation of a heat and cooling fluid exchange system between two buildings, where both thermal heat and cold can be exchanged. Figure 2-2 provides a schematical description of the winter and summer thermal exchange cases between the buildings designated as GMP1-2.5 and GMP1-2.3

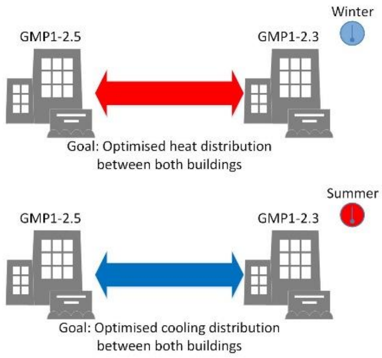

Figure 2-2: Schema of winter and summer thermal exchange between both buildings.

The workflow used to describe the project is called **PPR (product process resource)**. The idea of this workflow is to model a project before execution in its entirety and define requirements and deliverables required by the project (**product**). Then, processes required by the project to being able to provide the product (**process**) are modelled. Lastly the specific components necessary to enable the processes (**resource**) are modelled. It is planned to serve as a planning workflow for any professional environment. The workflow is used in building automation for the first time in this project.

Requirements (product) of the project are:

- Supply of GMP1-2.5 by GMP1-2.3 with heat or cooling (support or entirely) and vice versa.
- Reduction of operating hours of gas boilers, primary supply by heat pumps of GMP1-2.5
- Reduction of CO2 emissions and surplus energy disposal
- Maintaining reliable energy supply to both buildings (building and machine operation)
- Protection of buffer storage against discharge by energy transport necessary (heat pumps)

3 DESCRIPTION OF THE SOLUTION

After defining the requirements (product) with the customer (STIWA facility managers), the required processes to fulfil the requirements are designed. The goal in process modelling is to show all the processes that the system is able to provide, in an easy and understandable way. This can then serve as a communication basis with the customer to decide which processes of the system should really realise and which processes are not necessary.

A method for modelling processes are energy flow diagrams. The different squares represent a process. In this case, heat energy storage, cooling energy storage in both buildings and an energy transport process. A total of 14 different processes were identified in the initial planning process. Two of them were decided by the customers that they are not necessary.

The description of the proposed solution comprises firstly the hydraulic system, secondly the control of the hydraulic system and finally the software development for the control of the whole system.

3.1 Hydraulic System

After the process modelling, resource modelling was conducted. It is then analyzed how each of the components in the hydraulic system needs to be operated to enable the required processes. Figure 3-1 shows the proposed hydraulic scheme with controllers and components relevant to the operability of the system.

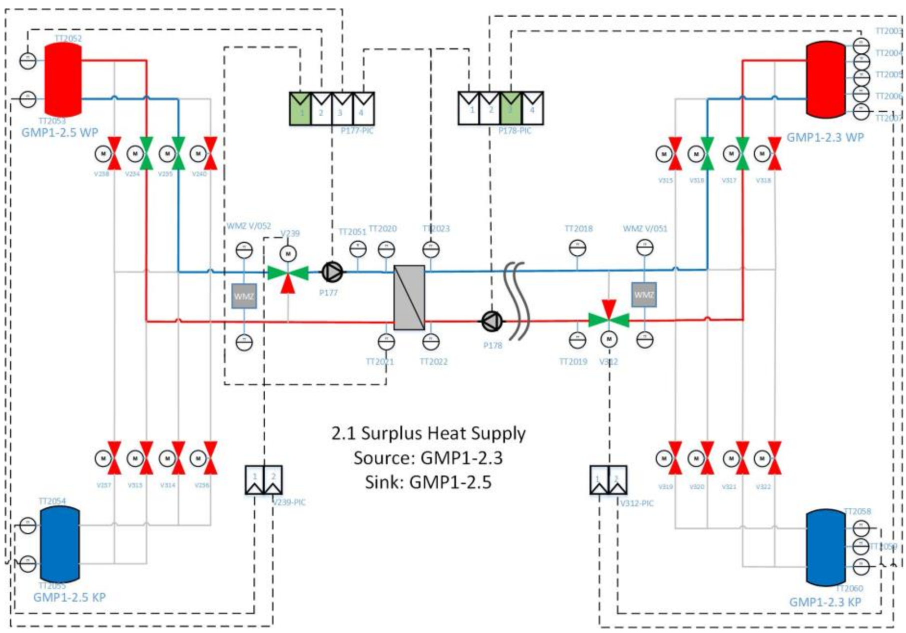

Figure 3-1: Control scheme of the energy transport system. PI-controllers are drawn with the actors they supply with a manipulated variable and from which sensor they get their actual values. The setpoints are drawn in a separate table.

The proposed energy transport system is connected to the hydraulic systems of GMP1-2.3 and GMP1-2.5 via heat and cooling water storages. In GMP1-2.5, there are heat pumps that provide thermal energy for the building and compressors with waste heat recovery systems. In GMP1-2.3, there is a gas boiler and cooling machines with waste heat recovery systems. The thermal energy produced is used in heating and cooling of the building and providing the production machines with process cooling. Waste heat is, at the moment, disposed of with free cooling devices in both buildings. The goal of the energy transport system is to make use of waste heat which would otherwise not be used and distribute energy efficiently between both buildings. The cheaper-to-operate heat pumps are therefore prioritised over the gas boiler if no waste-heat is available, for example.

With 8 valves per side, each possible way of fluid transfer can be operated. There are additional three-way valves near the recuperator connecting the hydraulic systems of GMP1-2.3 and GMP1-2.5. Those three-way valves are installed to provide an constant temperature in the reflux to the storage tanks without cooling or heating the heat storage or cooling water storage, respectively.

3.2 Control of the hydraulic

The result of resource modelling are different control schemes, one of them is shown in Figure 3-2. There is a control scheme of each process which shows the different components in active or inactive state.

An overview of all the required documents of each process can be seen in Figure 3-2.

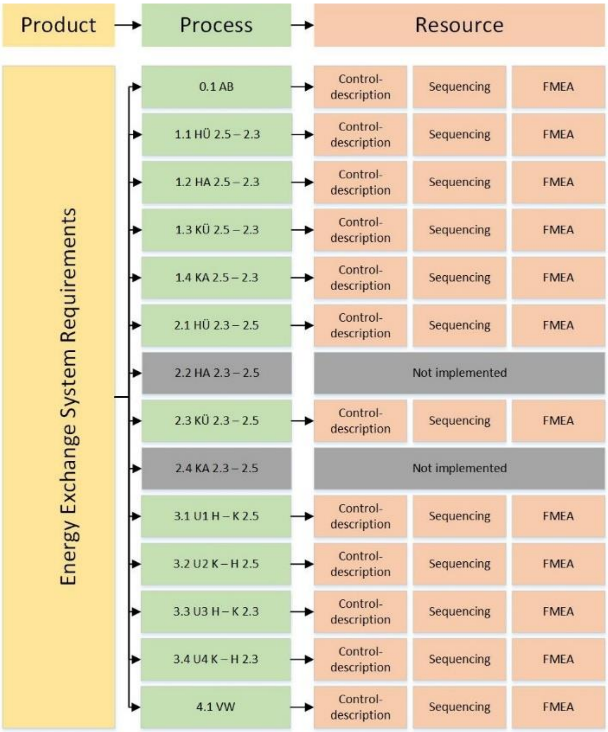

Figure 3-2: Overview of the required documents after resource modelling. Each process requires a detailed control description with switch conditions between processes and set values, a control scheme and a failure mode and effect analysis (FMEA). The designation of processes is an abbreviation of distributing heat (H) or cooling energy (K), surplus energy (Ü) or sole energy supply by one building (A) and transport switch processes (U)

Another important document made in resource modelling is a “Failure Mode and Effect Analysis” (FMEA). Possible failures and errors that can occur in the system in each of the different processes are analysed and reactions to those failures to ensure a secure and reliable operation of the system.

The processes implemented are heat and cooling energy transport from GMP1-2.3 to 1-2.5 and vice versa, each as a surplus energy supply or sole energy supply for both buildings with two processes being neglected.

With the help of an FMEA, one exemplary problem was identified. If the energy transport system is used for heat transport, and then cooling transport is required, the valve positions would be switched to enabling a flow into the cooling water storage. The transport system, on the side of GMP1-2.3, has 200 meters of pipe length, therefore a considerable volume of hot water now leads into the cold-water storage.

A reaction to this problem was found using an FMEA. The three-way valve is used to mix hot water with cold water from the cooling water storage and gradually reduce the temperature in the transport system without overloading the cold-water storage with hot water.

A possible result of a cold-water storage that was too hot is, that the cooling machines in GMP1-2.3 cannot be operated anymore, therefore the production machines cannot be operated.

Due to this error, four additional processes are required. If the energy transport requirement is switched from heat to cooling energy transport, the pipe system needs to be cooled or heated to mitigate the discharge of energy storage.

An additional process was designed to cover the pre-heating process of the pipe system with waste heat which would otherwise be disposed of during winter when heat exchange is more relevant than cooling energy exchange.

3.3 Software solution

The control of the system requires a software solution to solve a so called "language problem". Namely, the transcription of a system based on linguistic rule description in flow charts into a computer understandable code. As programming by coding (text-based) can be very complex and difficult to understand and increase the code developing and code maintenance, a graphical programming looks to be more adequate to use and understand in the context of hydraulic control. With only parameterising of predefined processes (shapes), it is anymore necessary to write code. To achieve this requirement, the programming tool GML (Graphic Motion Language) was chosen. This language allows the creation of SPS programme of the processes defined by PPR (Product Process-model Resources-model). The workflow of these programme is:

1. Checking process parameters for status change (trigger)
2. Decision-making in response to trigger (decision tree - management level)
3. Execution of the decision found (action)
4. Waiting for a new trigger

Trigger monitors the parameters of the system and determines the decision to be taken based on the decision tree.

4 RESULTS

4.1 Software

In this section we present some results of the operability of the software developed with GML. Figure 4-1 shows the sequence of operation previously introduced, by the case of an overshoot of the limit of temperature: Trigger, Decisions and Actions.

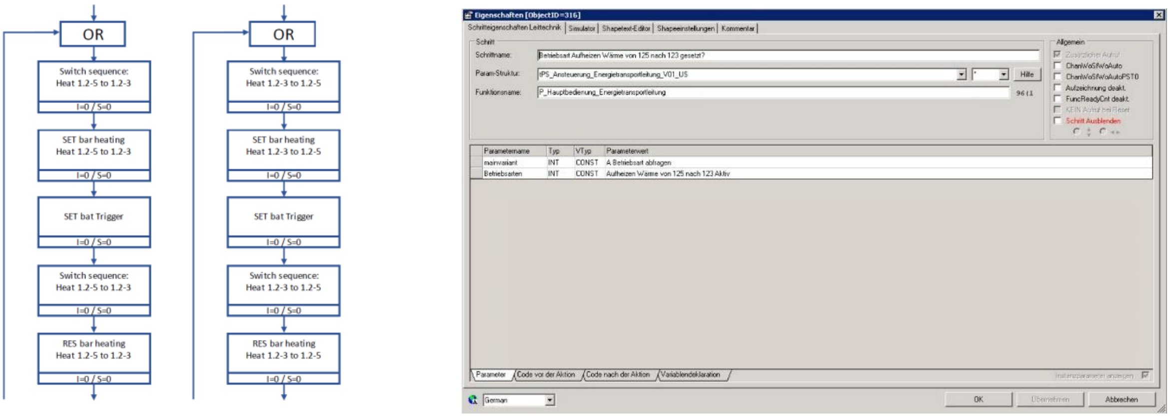

Figure 4-1: Trigger. GML operational working for an overstep of the system temperature.

The left side of Figure 4-1 shows the trigger generated by exceeding the limit of temperature. The parametrization of the query is depicted in the middle whether the cold buffer temperature falls below the limit value of 16°C again. The right side depicts the code template for the shape temperature query - frontend replaced with input of five parameters.

Trigger: By exceeding one of the setup limits, the control system triggers firstly the decision tree to run through. The most suitable operating mode is found by querying various triggers. And finally, an action to operate this mode is requested.

Decision trees: As shown in Figure 4-2.a, decision trees are based on binary yes/no decisions: divide processes into "small steps" to make many individual yes/no decisions, from which the modes of operation can be derived. This operability makes the system highly flexible and scalable: Programme can be expanded at any time with triggers, decisions, or actions.

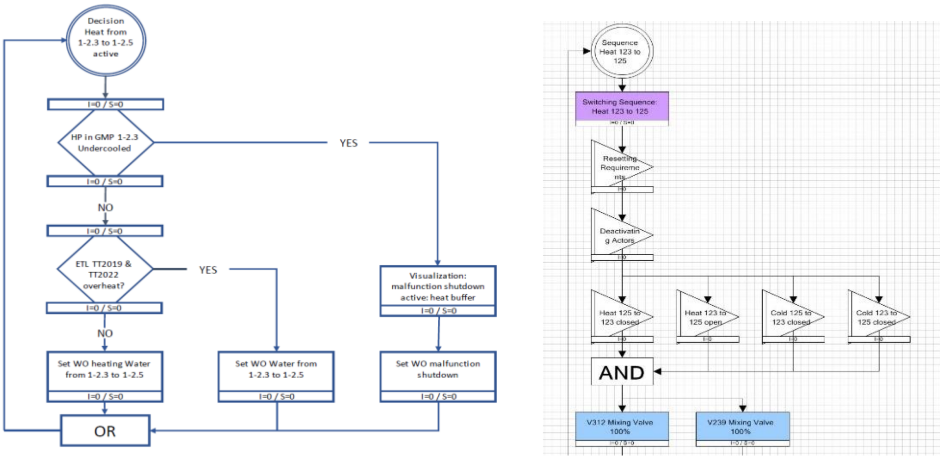

Figure 4-2: (a) Decision trees. Cuts of the decision trees triggered. (b) Actions. Setting the OM HÜ 2.3 - 2.5.

Figure 4-2.b depicts the outcoming action (HÜ 2.3-2.5): Setting the valves in the correct position, then activating the pumps. Each action includes the following operations: (a) it executes a decided operating mode (OM), (b) all components are brought into correct position, (c) possible setting of a time cascade/delay if necessary, (d) Termination conditions can be defined during the action (e.g. pipe break - stop pumps immediately, not after action), and (e) OM remains active until the decision tree triggers other OMs.

An extra aspect of the implementation to remark is the contribution of the software to the integral project planning. Figure 4-3 summarizes the PPR-Approach:

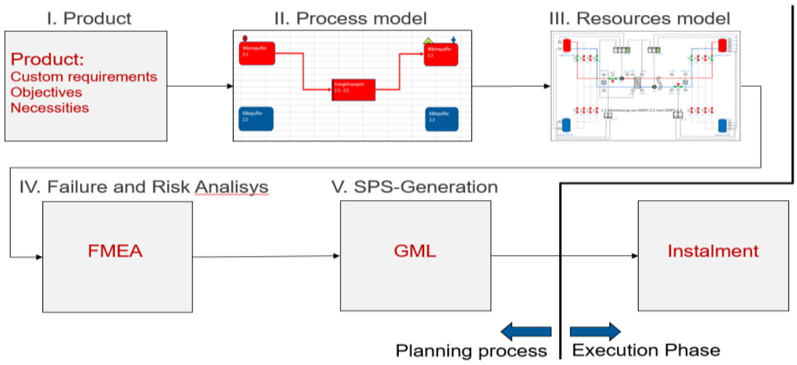

Figure 4-3: Integral project planning based on the generated PPR-Approach.

4.2 Measurement results

The energy transport system was implemented in March 2022, with a pump unit having mechanical problems leading to a delayed commissioning in May. The prioritized processes to be commissioned by the customers were the heat exchange processes to reduce required gas. Therefore, in summer, cooling energy exchange was not in commission, and there was no requirement for heat in both buildings, so there was no significant energy transport between the two buildings possible as of September 2022.

There are, however, measurement data available for the energy transport system starting from March, which provide important results of the operation of the energy transport system.

In Figure 4-4, an outcome from the data analysis is shown. The analysed data is from late March and shows the power measured at a heat meter in the energy transport system in GMP1-2.3.

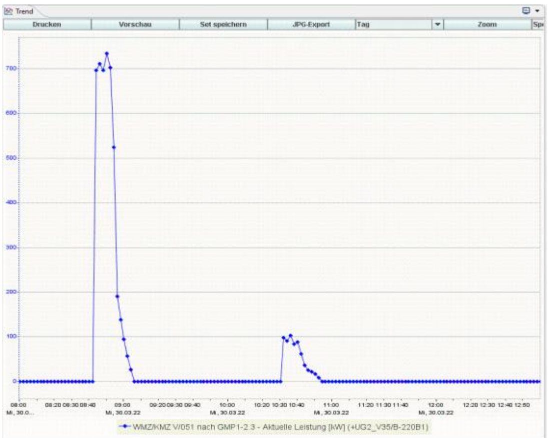

Figure 4-4: Thermal power measured at the heat counter on the side of GMP1-2.3 shows an instance of process switch from cooling to heating with a high thermal power peak

Due to cold water in the pipe system, a significant power peak is detected. The cold water in the energy transport pipe system has 10°C, the water used to heat the energy transport pipe system has 45°C. Without the controlled three-way valve switch process, 700 kW of thermal power is transported through the system despite being only commissioned for 220kW. The possibility of those power peaks from early commissioning attempts were already described in the FMEA during the PPR planning process. In this test, it was proven to be a problem. Otherwise, it could have occurred during operation and have led to more severe problems.

The main goal of the energy transport system was to reduce the operating time of a gas boiler in the building GMP1-2.3. The annual heat supply by the gas boiler which needs to be substituted is 317 MWh. The storage of waste heat in the energy transport system began on the 3rd of October, the amount of energy put into the energy transport system is 1750 kWh during a period of 17 days, shown in the figure below:

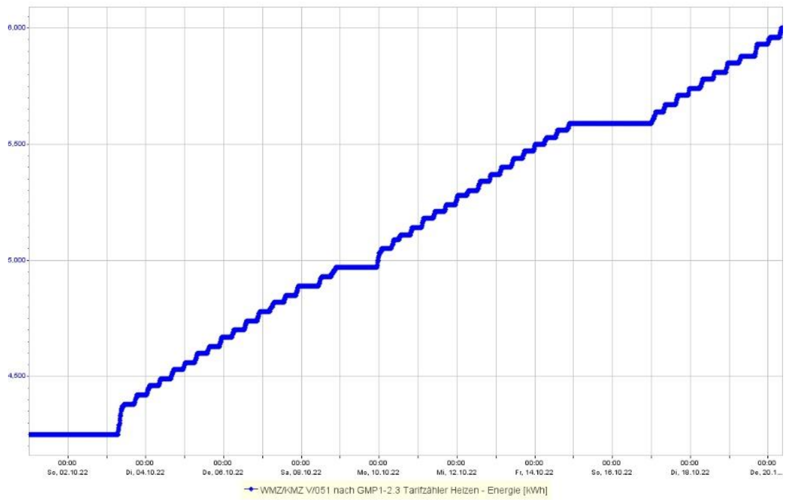

Figure 4-5: Energy meter data showing the amount of waste energy from machinery stored in the energy transport system

This amount of energy only comprises of waste heat produced by compressors and machinery instead of being disposed of via free-cooling devices.

At the time of writing this paper, there has not been a requirement for energy transport to substitute the heat supply of the gas boiler as waste heat was enough to heat the building. Therefore, the measured amount of energy shown in the Figure 4-6 is only a fracture of the gas boilers annual heat supply. However, if heat demand increases when the outside temperature decreases, the heat pumps of building GMP1-2.5 will be able to supply heat to building GMP1-2.3. The pipe system, pre-heated by waste heat, will lead to faster reaction time due to heat energy from the heat pumps being delivered faster to the heat storage unit in the building GMP1-2.3.

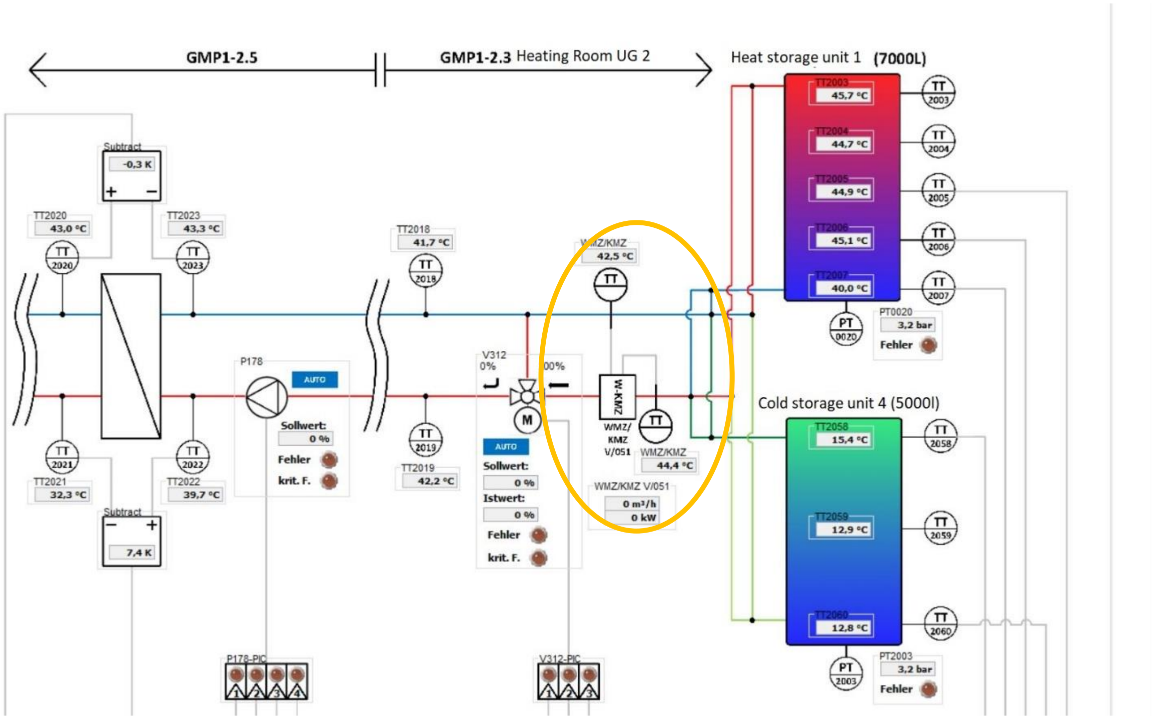

Figure 4-6: The energy measurement data is gained from the energy meter shown in this figure, indicated with an orange circle

5 CONCLUSIONS

In this paper we have presented a new methodology beyond of the state-of-the-art to increase the efficiency of the energy usability for the case of a bidirectional thermal exchange between two building based on a PPR modelling. Contributions of this new development are based on different pillars.

The first component of the solution deals with the identification of the requirements to satisfy. In this step, all possible processes will be firstly, identified and secondly, meticulous analysed to discard all of them, that will not be required.

The second stage starts by defining all the processes with help of energy flows diagrams. A graphical description of the energy flows allows a careful analysis of the project before it is implemented. And together with the use of standardised processes, it provides a documentation of the function of the project for the entire life cycle. This methodology is entirely independent of any software and allows to define objectives and non-objectives easily. Furthermore, it provides a Target-oriented solution by finding through precise "product definition". It also illustrates complex processes in a simple way through "process modelling".

The third phase comprises the transfer from the model into the control software. It selects control-relevant components by MSR through "resource modelling". The main advantages of the software tool GML lie on the graphical parameterisation instead of programming, on the problem-free traceability of the programme, and on its modularity, allowing programme extension.

Although the implementation of the whole solution is not already finished and several technical problems happened during some adaption processes, these were already detected by the software solution.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] EU countries' long-term strategies to meet their Paris Agreement commitments and the energy union objectives. [Online]. Available: https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-long-term-strategies_en. [Accessed 09 2022].

[2] Global Members of HPT TCP Annex 48. [Online]. Available: https://waermepumpe-izw.de/. [Accessed 09 2022]

[3] G. Koglbauer: District Heating by Heat recovery from the Brewing Process of the Brewery Puntigam, S. 17, 4. Oktober 2018. [Online]. Available: https://www.aee-intec.at/0uploads/dateien1354.pdf. [Accessed 09 2022]