Post Graduate Programme Renewable Energy Master Thesis

NUTS-3 Regionalization of Industrial Load Shifting Potential in Germany using a Time-Resolved Model

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Abstract

As power systems transition into higher shares of variable renewable energy, and use of conventional power plants decreases to meet emission reduction targets, demand for alternative flexible balancing tools such as load shifting increases. Characterizing the geographical distribution of such flexible balancing resources is important due to local limitations of transport capacities and increasingly decentralized power generation. The objective of this work is to estimate industrial load shifting potential in Germany with NUTS-3 spatial resolution using a time-resolved load shifting model previously developed by Kleinhans (2014), with open access to all input data, methodology, code, and results. The focus of analysis is on the potential for electrically intensive machines which manufacture industrial goods to provide load shifting (referred to here as industrial processes) because they are directly available for exploitation at present, while industrial process heat is investigated as a secondary topic as it is predominately supplied by fossil fuel, and thus requires future development to utilize. The four main research questions that are investigated are (1) whether NUTS-3 industrial process annual energy demand can be estimated using easily accessible data from statistical data bases or industry reports rather than more difficult to obtain plant specific data as has been used by the few previously published studies which investigate NUTS-3 industrial load shifting potential, (2) how the load shifting potential results using the selected approach compares with existing literature, (3) how NUTS-3 process heat load shifting potential can be estimated, and how the potential compares to industrial processes, and (4) how the load shifting potential for industrial processes will develop up until 2050.

To answer the first research question, three alternative methods of estimating NUTS-3 electrical energy demand for industrial process load shifting applications are developed and tested. It is found that the alternative methods are not able to estimate regional energy demand with sufficient accuracy in comparison to the plant specific characterization method. Plant specific data collected from a number of publicly accessible online sources such as company websites is instead used to estimate regionalized load shifting potential, along with other model inputs selected from a detailed literature review. The resulting annual average national estimated load potential is 376 MW positive balancing power, -871 MW negative balancing power, and 2682 MWh storage capacity. National rather than NUTS-3 load shifting potentials are compared to literature because NUTS-3 numerical results have not been published by the previous studies reviewed. The estimated load shifting potentials from this study are generally lower than previous studies.

A broad approach to estimating industrial process heat load shifting potential is taken; NUTS-3 total process heat demand is estimated, and different flexible shares of the total demand, as well as maximum load shifting duration values are tested to obtain a preliminary idea of the scale of the potential in comparison to industrial processes, as well as the NUTS-3 distribution. It is found that process heat power balancing potential exceeds the potential of industrial processes with a flexible share of just 2%. The NUTS-3 distribution of PH load shifting potential is more concentrated in the west area of Germany in comparison to industrial processes, and has a stronger time dependency.

Future load shifting potential for industrial processes is estimated using production and specific energy demand trends in recent history. It is projected that the potential of some applications increase, while other applications decrease or remain constant, but the overall positive and negative balancing power potential increases 18% by 2050 to 443 MW and -1032 MW, and storage capacity increases 20% to 3214 MWh.

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Declaration

I state and declare that this thesis was prepared by me and that no means or sources have been used, except those, which I cited and listed in the References section.The thesis is in compliance with the rules of good practice in scientific research of Carl von Ossietzky Universität Oldenburg.

Danielle Schmidt

Oldenburg, 27th of November 2019

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List of Acronyms

CHP combined heat and power

CSP concentrated solar power

CTMP chemi-thermomechanical pulping

DIME Dispatch and Investment Model for Electricity Markets in Europe

DR demand response

ELTRAMOD Electricity Transhipment Model

GHG greenhouse gas

IPCC United Nations Intergovernmental Panel on Climate Change

NUTS Nomenclature of Territorial Units for Statistics

PH process heat

REMix Renewable Energy Mix

RMSE root mean square error

SGW stone ground wood pulping

TMP thermomechanical pulping

VDP Association of German Paper Factories (Verband Deutscher Papierfabriken)

VDZ Association of German Cement Works (Verein Deutscher Zementwerke)

VRE variable renewable energy resources

WZ08 Wirtschaftszweige 2008

List of Symbols

e_y Annual energy demand [MWh]

Δt Time frame of management. Maximum duration of negative balancing power DR intervention [hours]

$E_{max}(t)$ Maximum positive energy storage capacity [MWh]

$E_{min}(t)$ Maximum negative energy storage capacity [MWh]

f Flexible component. The share of flexible load of the total load [%]

f_{dec} Percentage of maximum capacity used to calculate minimum load [%]

f_{inc} Percentage of free capacity which can be used for load shifting [%]

n_{flh} Number of full load hours [hours]

Λ Maximum capacity. The maximum load of a particular application [MW]

$P_{max}(t)$ Maximum charging power to the storage-equivalent energy buffer. In other terms, the available positive balancing power [MW]

$P_{min}(t)$ Maximum discharging power from the storage-equivalent energy buffer. In other terms, the available negative balancing power [MW]

p_y Annual production [tonnes]

p_{yc} Annual production capacity [tonnes]

$L(t)$ Scheduled load. The expected load of a particular application, without load shifting interventions [MW]

e_i Specific electrical energy demand [kWh/tonne]

s_{util} Average capacity utilization [%]

1 Introduction

According to the United Nations Intergovernmental Panel on Climate Change (IPCC) humankind is now at a time of unequivocal and rapid global warming (Allen et al., 2018). With the goal of strengthening the global response to climate change, the terms of the 2015 Paris Agreement were to pursue efforts to limit warming to 1.5°C of pre-industrial temperatures (Allen et al., 2018). Efforts to achieve this goal are becoming increasingly critical, as in 2017 human-induced warming reached 1°C above pre-industrial levels; if warming continues at the current rate, 1.5°C warming will be reached in 2040 (Allen et al., 2018).

In the pursuit of reducing greenhouse gas (GHG) emissions, the global electrical power sector is making remarkable progress in its transition to renewable energy (Zieher et al., 2015). Installations of renewable energy capacity has been greater than the combined installation of fossil fuel and nuclear generation for four consecutive years, and renewable energy now constitutes 33% of global generation capacity (REN21, 2019). Wind and solar energy in particular are becoming increasingly prevalent in electricity supply systems; in 2018 solar photovoltaics and wind accounted for 55% and 28% of the global renewable energy capacity installed, respectively (REN21, 2019). Wind and solar energy are referred to as variable renewable energy resources (VRE) because their energy output varies strongly according to wind conditions and solar irradiation, and are not dispatchable; this is in contrast to controllable production units such as conventional power plants, hydroelectricity, and biomass (Zieher et al., 2015).

1.1 Demand Response

Due to the intermittent and non-dispatchable nature of VRE, the increase in integration of VRE is a significant challenge for the operation of power systems (Gils, 2015). Fluctuations in VRE generation and system demand need to be balanced by methods such as dispatchable renewable generators, conventional power plants, energy storage, demand response, and long-range balancing via power transmission (Müller and Möst, 2018). At present, fluctuations in VRE are balanced mainly by conventional power plants, transmission grids, and pumped hydro plants (a form of energy storage) (Gils, 2015), while demand response (DR) currently plays a minor role (Valdes et al., 2019). However, the demand for balancing will increase in the future, and the use of conventional power plants will simultaneously need to be reduced to meet emission reduction targets, thus additional balancing technologies will be needed (Gils, 2015). The focus of this thesis is on DR as a balancing tool. In practice, DR is just one piece of the puzzle, as a combination of different flexible balancing methods will be needed for effective operation of systems with a high share of VRE (Müller and Möst, 2018; Gils, 2015).

Demand response is defined as "changes in electric use by demand-side resources from their normal consumption patterns [...]" (Wight et al., 2011). Demand response utilizes available elasticity of consumer demand, which is generally provided by thermal inertia, demand flexibility, or physical storage (Gils, 2015; Müller and Möst, 2018). The advantages of DR compared to other balancing methods are the low infrastructure requirement, low environmental impact, and that it avoids the need for additional energy conversion (Gils, 2015). In addition, from a system perspective, DR is an efficient option because it reduces overcapacities (Müller and Möst, 2018). The primary disadvantages of DR are the intermittent temporal availability of loads, and limitations on shifting times (Gils, 2015).

There are two classes of DR which can be differentiated, which are demonstrated visually in Figure 1: load shifting, and load shedding (Müller and Möst, 2018; Gils, 2015). Load shifting applies to loads which may be shifted from one time to another; load shedding is associated with loads which may be reduced, but for which cannot be compensated for at another time

(Paulus and Borggrefe, 2011). In load shifting, loads can be moved to either periods of low demand, or high renewable energy feed in (Müller and Möst, 2018). Load shedding is typically executed during peak demand periods (Müller and Möst, 2018).

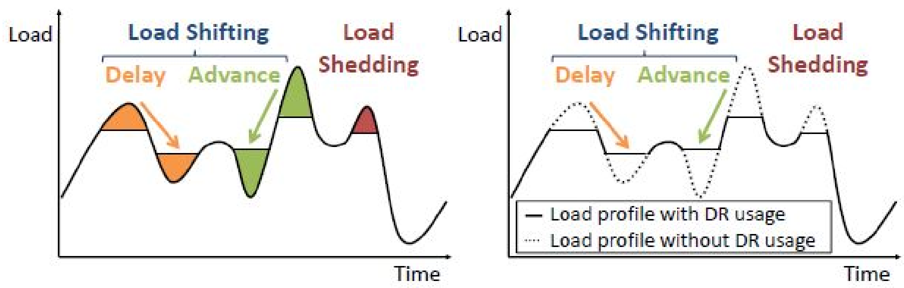

Figure 1: Mechanism and impact of load shifting and load shedding (Gils, 2015)

1.2 Demand Response Modelling and Open Modelling

In the context of the shift of power systems towards increasing shares of VRE generation and the increasing need for flexibility, characterizing the potential of DR is valuable. Demand response modelling is also useful in terms of integration into energy system models (Paulus and Borggrefe, 2011; Gils, 2015; Müller and Möst, 2018). Energy system models are simplified representations of real technologies and systems; different energy system models have been developed by various institutions across the world (Gils, 2015). Energy system models are important tools used by policy makers, research communities, and large energy supply companies to explore the effect of different boundary conditions and to simulate policy and technology choices (Herbst et al., 2012). Integration of DR modelling capability into energy system models simply expands the utility of these models.

In energy system modelling, geographic allocation of supply and demand is essential due to limitations of transport capacities (Gils, 2015). However, the focus of spatial resolution development has been on the supply side, with the demand side receiving significantly less attention (Elsland et al., 2015). This background, especially in the context of increasingly decentralized power generation, and a corresponding need for local flexibility (Elsland et al., 2015), emphasizes the importance of high spatial resolution DR modelling. In addition to spatial resolution, temporal resolution is important in energy system modelling to reflect daily and seasonal variations (Gils, 2015).

Together with spatial and temporal resolution, data and code accessibility is also a key focus of this study. While being historically closed and proprietary, there has been a notable shift towards open code and open data in recent years in energy system modelling (Pfenninger et al., 2018; Morrison, 2018). Open code and open data is advantageous because it improves transparency and reproducibility, and increases productivity through reduction of parallel efforts (Pfenninger et al., 2018).

1.3 State of Knowledge

Multiple studies which have analyzed DR potential of different sectors in Germany have highlighted that DR potential in industry is particularly attractive due to comparably low investment costs and ease of exploitation (Klobasa, 2007; Gils, 2015; Müller and Möst, 2018). The key difference between industry and other sectors is that the industrial sector has a relatively small number of large electricity consumers, whereas the residential and commercial sectors have a large number of small electricity consumers. According to VDE (2012), the average electricity demand per industrial customer is approximately 119 times larger than other customers. This high energy demand nature of industry is advantageous, as the specific cost per MW is significantly reduced for facilities with higher capacity (Klobasa, 2007). In addition, with industrial plants it is easier to establish a connection to enable communication with and control of the application in question, which is of high importance (Klobasa, 2007).

Within industrial DR, there is also the distinction between load shifting and load shedding applications. With load shedding, the load is simply lost and cannot be recovered; in industry this lost load corresponds to lost production volume (Paulus and Borggrefe, 2011). The lost production volume must be economically compensated for if the load shedding potential is to be utilized (Paulus and Borggrefe, 2011). Several studies have indicated that in most cases the activation costs for industrial load shedding applications are prohibitively high, and although a large potential in terms of reducible power exists, it is not economically accessible (Paulus and Borggrefe, 2011; Müller and Möst, 2018). In addition, lost production volume would decrease the absolute quantity of the corresponding product produced by Germany (ex. steel, aluminum), which could be detrimental to other sectors such as the construction industry if accessed in high enough quantities. In favour of the economic and logistic viability of industrial load shifting, this study will focus exclusively on industrial load shifting applications. However, because most studies investigate both load shifting and shedding, the general term DR will continue to be used when referring to literature.

German DR potential has been a research topic since 2005 (Stadler, 2005; Müller and Möst, 2018), and the first detailed investigation of industrial DR applications and DR modelling in Germany was performed by Klobasa (2007). Since then, industrial DR potential has been estimated and modelled by a reasonably large number of publications: Paulus and Borggrefe (2011), VDE (2012), Gruber et al. (2014), Gils (2015), Müller and Möst (2018), and more. In the above mentioned DR studies, DR is typically characterized in an application specific manner (ex. cement milling, wood pulping). This is because each application has its own unique characteristics which can only be fully accounted for when considered individually. A second related research topic is modelling of demand, such as in Beer (2012), because demand is a critical component of DR modelling.

One fundamental challenge in demand modelling, and thus DR modelling, especially at higher spatial resolution, is data availability (Elsland et al., 2015; Wittekind, 2019). The challenge intensifies further when investigating application specific demand. The question is: in the context of limited data availability, how can application specific demand be best estimated and modelled?

In previous studies, there are two main approaches to estimating application specific industrial demand: (1) by using production data [tonnes] and specific energy demand [kWh/tonne] (Klobasa, 2007; Gruber et al., 2014; Gils, 2015; FfE, 2016; Müller and Möst, 2018)[1], and (2) through conducting industry surveys (Paulus and Borggrefe, 2011; VDE, 2012). Industrial production data is available on a Nomenclature of Territorial Units for Statistics (NUTS)-0 basis[2] from the federal statistic office of Germany (Statistisches Bundesamt) or from industrial associations, but not for higher spatial resolutions. To estimate production of different industrial products at higher spatial resolution, the methodology of Gils (2015), Gruber et al. (2014), and FfE (2016) is to identify the location and production of each plant individually through publications from industrial associations and companies to the furthest extent possible; this method is referred to in this work as the plant specific characterization method. As

[1] FfE (2016) uses the results of Gruber et al. (2014) for industrial processes and is written by the same first two authors, but FfE (2016) has a more detailed methodology description and therefore is useful to refer to.

[2] Refer to Section 2.1.2 for more information on the NUTS classification system.

the data is collected from publicly published documents, it is open data. However, the amount of work and time required to gather site specific information from such a large number of sources is significant. Similarly, conducting industry surveys requires a considerable degree of work and time, and carries an additional question of the openness of the collected data. The relatively manual and time consuming nature of data gathering under these two methods is in contrast to methods used to estimate regional residential and commercial load shifting application demand, which typically utilize available statistical data (Gils, 2015; FfE, 2016). The more difficult to access to industrial data serves as a hindrance for estimation and modelling of industrial load shifting, both to conduct as a one-time analysis as well as to keep updated.

In addition, few studies have estimated or modelled industrial process load shifting potential at a resolution higher than NUTS-0 for Germany. Gils (2015) conducts analysis at a NUTS-3 spatial resolution across Europe, but presents results at NUTS-0. Gruber et al. (2014) estimates NUTS-3 industrial DR potentials for Germany and presents them graphically, but the results are not numerically accessible, and the methodology is not transparent and therefore not reproducible. In addition, temporal resolution is not taken into account.

There are three main categories of industrial load shifting found in literature: industrial processes, cross-sectional technologies, and heat. What are referred to as industrial processes in this report are electrically powered machines which manufacture industrial goods. Examples of typically considered industrial processes in existing literature are cement milling, and mechanical wood pulping. Cross-sectional technologies are applications which exist in industry, but also exist in other sectors such as commercial. Commonly considered cross-sectional technologies are ventilation and refigeration/freezing. Industrial heat applications include space and hot water heating, and process heat.

The focus of this work is on industrial processes as load shifting applications. Cross-sectional technologies are excluded due to scope constraints and differing methodology, but are also a viable load shifting application with considerable potential (Gils, 2015). The industrial processes and cross-sectional technologies mentioned above are presently existing, electrically supplied applications which are directly available for exploitation. On the other hand, heat supply constitutes a majority share of industrial energy demand (74%), but presently is predominately supplied by fossil fuel sources and currently has low economic potential due to higher electricity prices in comparison to natural gas (Gruber et al., 2015). Nonetheless, industrial heat demand will need to be met by electricity in the future if emission targets are to be met (Gruber et al., 2015). Theoretical industrial heat load shifting potential is therefore compelling to evaluate, and will be a secondary topic of this report.

1.4 Objectives, General Methodology, and Structure of Thesis

From the reviewed literature, there was no one study that could be identified which addressed both temporal and spatial resolution of industrial load shifting in a transparent and transferable manner suitable for integration into an energy system model. To address this identified research gap, the overall objective of this thesis is to model temporally resolved industrial load shifting potential in Germany with NUTS-3 spatial resolution, and open access to all input data, methodology, code, and results. The focus of investigation is on industrial processes; cross-sectional technologies are excluded, and industrial heat is a secondary topic. Additionally, to address the matter of difficult to access industrial data using the plant specific characterisation method or industrial survey method found in existing literature, alternative methods of estimating NUTS-3 energy demand for industrial processes using more easily accessible data will be investigated. In the pursuit of this objective, the following research questions will be answered:

1. Can an alternative method to estimate NUTS-3 industrial process annual energy demand using easily accessible data from statistical databases or industry reports be identified, which produces results comparable to the plant specific characterization method?
2. How do the industrial process load shifting potential results using the selected approach compare with those estimated by other studies?
3. How can NUTS-3 industrial heat load shifting potential be estimated, and how does the potential compare in relation to industrial processes?
4. How will industrial processes load shifting potential develop in the future until 2050?

To model the load shifting potentials, a time-resolved DR model framework previously developed by Kleinhans (2014) will be used. The model requires three fundamental inputs: the load curve prior to any load shifting interventions, the maximum load shifting time (referred to as time frame of management), and maximum capacity. In practice, the load curve is comprised of two inputs because it is typically modelled using an absolute annual energy demand figure and a scalable load profile (Gils, 2015; Müller and Möst, 2018; Wittekind, 2019). An additional fifth model input, referred to as the flexible component [%], will be added to the model framework in this work to enable modelling of technical potential. All of the model inputs except annual energy demand will be obtained or adapted from literature. In doing so, a detailed literature analysis is performed with the purpose of identifying the most appropriate and accurate model inputs.

Annual energy demand is the key parameter in this work because the regionalization of the load curves and maximum capacity, and thus the load shifting potential, are dependent on it. All other model inputs are constant across the regions. To address the first research question, NUTS-3 industrial process specific annual energy demand will first be estimated using the conventional plant specific characterization method, and then using three developed alternative approaches suitable for use with easily accessible data.

The progression of this report is structured as follows. In Section 2 the theoretical background of the project is established, including a broad overview of literature, a technical description of the industrial processes selected for analysis, and then an in-depth literature review on the methodology of obtaining, or the values of the inputs necessary for the time-resolved load shifting model. Section 3 describes the methodology of the current project in detail: the time-resolved load shifting model used, selection of required model inputs from literature previously presented in Section 2, the plant specific characterization method, and presentation of three alternative methods utilizing easily accessible data to estimate process specific NUTS-3 annual energy demand. Section 4 first presents the results of the three alternative methods for estimating process specific NUTS-3 annual energy demand, and compares them to the results of the plant specific characterization method. In the case that one of the alternative methods of estimating NUTS-3 annual energy for industrial processes replicates the results of the plant specific characterization method well, then the results of that method will be fed into the load shifting model along with the remaining inputs adapted from literature to estimate application specific NUTS-3 load shifting potentials. If the alternative methods are not successful, then the results of the plant specific characterization method will be used instead. The industrial processes load shifting potential results will be analyzed against those of previous studies. The results of the industrial heat component, and future projection of industrial processes load shifting potentials up to 2050 will also be presented and discussed. The results of, and conclusions drawn from this work will be summarized in the final Section 5.

2 Theory

This theory section is comprised of three subsections. In the first subsection, a conceptual introduction to load shifting modelling is given, including the different ways in which load shifting is considered, and the fundamental concepts of temporal and spatial resolution. The second subsection delves into detail on industrial process load shifting: an overall analysis of existing literature, technical descriptions of industrial processes selected for study, and a model input specific literature review to enable identification of the most suitable methodology or values later in Section 3. The third subsection presents a short background on industrial heat demand and load shifting. It must be noted here that all literature reviewed has been limited to German focused, or German authored studies; international DR studies are not considered.

2.1 Load Shifting Modelling

By increasing system demand at one time, and decreasing demand at another time, load shifting applications function similar to an energy storage device and is typically modelled as such (Paulus and Borggrefe, 2011; Gils, 2015; Müller and Möst, 2018). Analogous to any energy storage device, a load shifting application has a maximum charging (increase in load) and discharging power (decrease in load), and storage capacity (Kleinhans, 2014). Note that increasing load and decreasing load are also referred to as positive and negative balancing power in this report. The quantification of these three properties are what are considered to be load shifting potential (Kleinhans, 2014). Unlike conventional energy storage, the maximum charging/discharging power and storage capacity for load shifting applications is time dependent as a result of the time dependent nature of the loads themselves (Kleinhans, 2014).

Not all studies investigate load shifting potential through computer modelling; the most common applications of computer models are to account for temporal and/or spatial resolution, and for investigating economic potentials using market simulations. Some studies estimate national non-time-resolved technical load shifting potential using basic calculations or industry surveys (Klobasa, 2007; VDE, 2012).

Few studies in the literature reviewed analysed all of the components of load shifting potential. Negative balancing power is typically the focus. Some studies do not report positive balancing power potentials (Klobasa, 2007; Gruber et al., 2014; Müller and Möst, 2018), which is a limited approach because the positive and negative balancing power potential for a given application is different in almost all cases (Paulus and Borggrefe, 2011; VDE, 2012; Gils, 2015).

Storage capacity is also considered in different ways by different studies. Several studies define industrial load shifting storage capacity as the energy equivalent of the physical storage capacities for industrial end products (ex. cement, paper) (Paulus and Borggrefe, 2011; VDE, 2012). If energy storage capacity is defined as the physical product storage capacity, then it is inherently constant. However, this is an incomplete perspective, as product storages cannot be expected to be empty or full at all times, and there may be additional factors which limit energy storage capacity. Typically, storage capacity is determined from the load and a defined shifting time (Klobasa, 2007; Gils, 2015; Müller and Möst, 2018).

2.1.1 Temporal Resolution

Out of the reviewed studies, Klobasa (2007), Gils (2015), and Müller and Möst (2018) perform time-resolved analysis of load shifting potentials. Time resolved analysis is important because load shifting potentials can vary over time depending on the load profile of a particular application (Gils, 2015; Müller and Möst, 2018). Figure 2 demonstrates the variability of load shifting potentials over time.

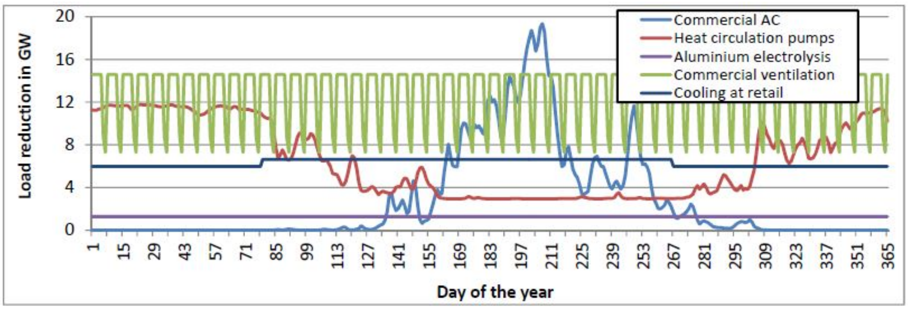

Figure 2: Time-resolved load reduction potential (Gils, 2015)

Time resolved analysis is more difficult than non-time resolved analysis, and requires the use of load profiles and some form of computer modelling (Klobasa, 2007; Gils, 2015; Müller and Möst, 2018). If a study does not perform time resolved analysis, single value maximum load shifting potentials are typically reported.

Klobasa (2007), Gils (2015), and Müller and Möst (2018) use 1 hour temporal resolution. The current work will also use 1 hour temporal resolution, when practicable based on available information and data.

2.1.2 Spatial Resolution and Regionalization

Spatial resolution and regionalization are two closely related terms. Spatial resolution can generally be defined as the smallest geographical unit of reference. Regionalization is defined as "the allocation of information/data to different regions of a territory whereby regions are geographically defined units" Elsland et al. (2015). Thus information is regionalized according to a selected spatial resolution.

The spatial resolution selected for use in this study is NUTS-3. NUTS is a hierarchical regional classification system in the European Union used for statistical and political purposes (Eurostat, 2018), and is commonly used in regional modelling studies to describe spatial resolution (Gils, 2015; Elsland et al., 2015; Wittekind, 2019). The NUTS system provides simple, standardized terminology for administrative units which is valid and understandable for all countries. Table 1 provides a clarification of the NUTS system as it applies to Germany.

Table 1: NUTS classification system in Germany (Eurostat, 2018)

NUTS term	English term	German term	Number in Germany
NUTS-0	Country	Nationalstaat	1
NUTS-1	State	Bundesland	16
NUTS-2	District	Regierungsbezirk	38
NUTS-3	County	Landkreis	401

2.2 Industrial Process Load Shifting

This section presents and analyzes the results of the literature review on industrial processes. First, a general overview of six studies important to the development of the current work is provided. Note that the list of literature reviewed here is not exhaustive; there exists additional studies on DR potential in Germany which have not been reviewed here. Following the overview of literature, a description of the industrial processes analyzed in this work is provided, based on information gathered from literature and industrial association publications.

Subsequently, a detailed literature review regarding the five required inputs for the time-resolved load shifting model: the time frame of management, flexible component, load profiles, annual energy demand, and maximum capacity is presented. Careful review and analysis of literature is important in this work due to the reliance on existing literature to establish appropriate methodology for generating the model inputs. Time frame of management and the flexible component are both single value, non-regionally dependent model inputs. In contrast, annual energy demand and maximum capacity are regionally dependent, and require subsidiary model inputs and data to calculate. The load profiles may or may not be regionally dependent, depending on what factors are taken into consideration. For example, temperature dependent load profiles result in regionally dependent load profiles. The purpose of the detailed model input literature review is to provide the basis for selection of the most appropriate values of, or methodology of determination for the model inputs, to be established in Section 3.2.

2.2.1 Overview of Literature

Six main studies were reviewed and utilized in the development of this work: Klobasa (2007), Paulus and Borggrefe (2011), VDE (2012), Gruber et al. (2014), Gils (2015), and Müller and Möst (2018).

Klobasa (2007) investigates the techno-economic DR potential with the focus of analysing the role of DR in contributing to the integration of of wind energy. The primary importance of Klobasa (2007) is the technical description and analysis of different industrial DR applications, and the provision of a variety of DR parameters. Following the technical assessment, cost parameters for the DR applications are characterized, and model simulations are conducted with different shares of wind energy. Analysis is performed with NUTS-0 resolution. Temporal resolution of the DR applications is conducted within the model. A library of 27 industrial load profiles previously developed by Fraunhofer Institute for Systems and Innovation Research was used, however the load profiles are not made accessible. Only an example aggregated industrial load curve for a summer and winter workday are presented. In the model simulations and subsequent analysis, all industrial DR applications are aggregated, and considered as suitable for load shedding only, thus limiting the applicability to the present work.

Paulus and Borggrefe (2011) specialize on industrial DR potential. Analysis is performed with NUTS-0 resolution, with no temporal resolution. They first present technical DR potentials on the basis of an industry survey conducted between 2008 and 2009, and then use a linear optimization model Dispatch and Investment Model for Electricity Markets in Europe (DIME) along with economic parameters also collected from the industry survey to simulate the economical DR potential of the selected industrial applications in 2020 in terms of capacity and call probability, as well as system cost savings. An interesting result from the economic simulations by Paulus and Borggrefe (2011) is that only the potentials from the load shifting applications were utilized as a result of the prohibitively high costs of lost load for load shedding industry, and contrastingly low opportunity costs of shifting applications due to the ability of these industries to recover the load.

VDE (2012) provide a thorough technical description of different industrial load shifting and shedding technologies, and their current status in Germany. Then, using an industry survey they estimate theoretical and technical DR potentials in terms of positive and negative balancing power, and energy storage capacity in Germany with NUTS-0 spatial resolution, and no temporal resolution. From the results of the industry survey, they report that the technical potential is equal to the theoretical potential (VDE, 2012). The base year of analysis is 2010, and in contrast to the residential and commercial sectors, VDE (2012) does not perform future estimations of industrial DR potential for 2020 and 2030 due to the dependency of industry potentials on the political and economic environment.

Gruber et al. (2014) is the only study reviewed which analyses and presents NUTS-3 DR potential for industrial processes in Germany. Each individual plant location is characterized, allowing for high spatial resolution. Application specific negative balancing power is presented graphically. Positive balancing power, storage capacity potential, and temporal resolution are neglected. In addition, the methodology behind the calculation of the DR potentials is not made clear.

Gils (2015) performs a comprehensive temporally resolved Europe-wide estimation of technical DR potentials for a variety of different applications. The hourly resolution used is 1 hour, and although the methodology of Gils (2015) allows for at least NUTS-3 spatial resolution, the industrial DR results are presented with NUTS-0 resolution. Gils (2015) investigates six different industrial load shifting applications, which is the highest number found across the reviewed studies. The methodology pursued by Gils (2015) is to identify individual plant locations and corresponding production capacities; however, out of the industrial load shifting applications investigated, he is only able to do this partially for cement plants. For the remainder of the industries, Gils (2015) allocates DR potentials using NUTS-3 employment statistics. The base year for analysis is 2010, with future estimations for 2020, 2030, and 2050. With the exception of the method used to estimate industrial production capacity, Gils (2015) provides clear and transferable methodology, along with a comprehensive set of model parameters and load profiles. Following the assessment of technical DR potentials, energy system model Renewable Energy Mix (REMix) is used to perform techno-economic simulations for nine 2050 scenarios with different renewable energy shares, and use of other balancing options such as power-to-gas, concentrated solar power (CSP), and grid extension to analyse the utilization of DR and combined heat and power (CHP).

Müller and Möst (2018) investigate DR potentials with the aim of determining whether DR is available during peak load periods, and the extent of utilization of DR potentials in future scenarios with different renewable energy shares. Temporally resolved analysis is performed with 1 hour resolution, and NUTS-0 spatial resolution. DR potential in 2013, as well as future DR potentials in 2035 and 2050 are estimated. A variety of model parameters and load profiles are provided, but the resulting DR potentials for industry applications are not numerically ascertainable from the presented figures. In addition, the results presented are for negative power balancing potential only. Following a first theoretical based analysis of DR potential, Müller and Möst (2018) then use electricity market model Electricity Transhipment Model (ELTRAMOD) to perform energy system simulations taking technical restrictions on DR into account to project the share of exploited DR potential and effect on the residual load curve. The exploitation of industrial load shifting applications is projected to be lower than that of load shedding applications, however the simulations do not take into account activation costs, which are noted to be very high for shedding applications. A previous study coauthored by Müller demonstrated that load shedding is cost effective only for a few hours a year (Müller and Möst, 2018).

Table 2 provides a concise summary of the properties of the DR studies selected for review, including the industrial load shifting applications considered. The applications selected as load shifting applications in the table as well as in the present study are based on the applications selected by Gils (2015) because it is the most extensive selection of applications found in the studies reviewed, and was developed based on the author's own extensive literature review. Calcium carbide production (CaC_2) is excluded from the present study because no production data for it could be found in government statistics, and from the results of Gils (2015) the potential for CaC_2 production load shifting is low in Germany compared to the other applications.

Table 2: Overview of selected studies

Study	Spatial resolution	Temporal resolution	Applications: cement/wood pulp/recycled pulp/paper/CaC_2/air	Openness and reproducibility
Klobasa (2007)	NUTS-0	1 hr	✓/✓/ ✓/ ✓/ - / ✓	+
Paulus and Borggrefe (2011)	NUTS-0	-	✓/✓/ - / - / - / -	+
VDE (2012)	NUTS-0	-	✓/✓/ - / ✓/ - / -	+
Gruber et al. (2014)	NUTS-3	-	✓/✓/ - / - / - / -	+
Gils (2015)	NUTS-0	1 hr	✓/✓/✓/✓/✓/ ✓	++
Müller and Möst (2018)	NUTS-0	1 hr	✓/✓/ - / - / - / -	++
Present study	NUTS-3	1 hr	✓/✓/✓/✓/-/ ✓	+++

There is some variation in the classification of which industrial processes are defined as a load shedding application versus a load shifting application in literature, and no precise definition could be identified. However, the general properties that make an application suitable for load shifting are: storability of the produced good, flexibility in the production process, and not fully exploited production capacity (Klobasa, 2007; Paulus and Borggrefe, 2011). In addition, high energy intensity is an important qualifier of industries which are considered suitable for DR (Paulus and Borggrefe, 2011; Gils, 2015). If a particular industry has high energy intensity, and high electricity costs in relation to the value of the good being produced, then there is higher motivation to participate in DR markets (Paulus and Borggrefe, 2011).

2.2.2 Description of Processes

The five industrial process load shifting applications to be assessed in this work are: cement milling, mechanical wood pulping, recycled paper pulping, and air separation. Each application is a distinct, controllable component in the production chain for the relevant industrial product. In this section, each load shifting application will be explained in the context of the overall production chain, and the flexibility of each application will be discussed.

Cement Milling

Cement milling is the grinding of cement clinker and supplementary materials such as gypsum into cement powder (VDE, 2012; Klobasa, 2007; Paulus and Borggrefe, 2011). Cement milling is the final process in the cement production chain, in which the upstream processes include crushing and milling of raw materials, and burning of the raw material powder in a kiln to produce cement clinker, as shown in Figure 3. Figure 3 also highlights the role of different product storages throughout the production chain.

The studies reviewed are split on what components of the cement production chain are suitable for DR. According to Klobasa (2007), both the raw material crusher and mill, as well as the cement mill are suitable for DR. Gruber et al. (2014) also considers raw mills and cement mills as suitable for DR. Gils (2015) does not clarify what parts of the cement production chain are considered, but the specific energy demand selected implies the entire production chain. On the other hand, according to VDE (2012), the raw material crusher and mills are unsuitable for DR because the storage sizes in the raw material and raw meal phases are insufficient, in contrast to the very large cement clinker and cement storages. Paulus and Borggrefe (2011) and Müller and Möst (2018) also consider only cement mills as suitable for DR. In the context of this split between previous studies, because Paulus and Borggrefe (2011) and VDE (2012) are the two studies reviewed which are based on industry surveys and thus are assumed to have more accurate industry information, it is assumed for the purposes of this work that only cement milling is suitable for load shifting. This is also the more conservative assumption.

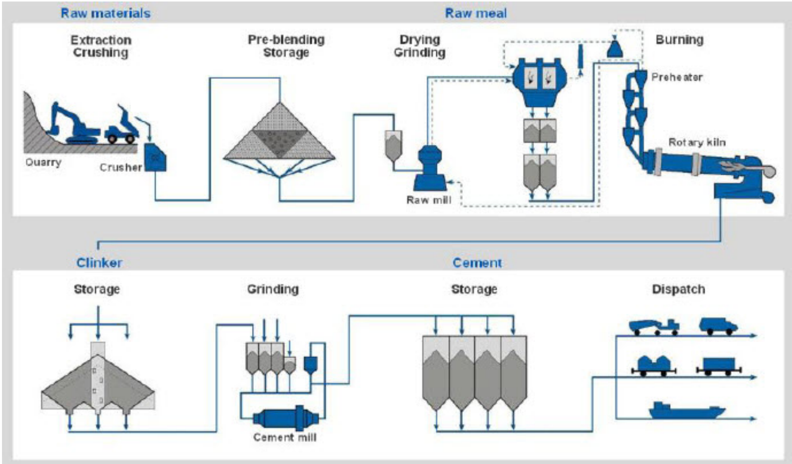

Figure 3: Cement production chain (IEAGHG, 2013)

Klobasa (2007) and Paulus and Borggrefe (2011) state that cement milling is highly flexible, with ramping-up and shut-down possible in minutes, and minimal restrictions on the production process. VDE (2012) expresses a more conservative view on the flexibility of cement mills, saying that ramp-up and shut-down is achievable within 30 and 15 minutes respectively, and that discontinuous cement milling (with repeated shut-downs and ramp-ups) can negatively affect plant efficiency and operating costs because during start up there is a risk that insufficient quality cement will be produced that must be re-milled at a later time.

Mechanical Wood Pulping

The first step in the paper-making process is pulp production (Klobasa, 2007; VDE, 2012). There are three main methods of producing pulp: mechanical pulping (most commonly stone ground wood pulping (SGW), thermomechanical pulping (TMP), and chemi-thermomechanical pulping (CTMP)), chemical pulping, and recycled paper pulping (Klobasa, 2007; VDE, 2012). Chemical pulping is not considered as suitable for load shifting by all reviewed sources, and thus will not be discussed further. Recycled paper pulping will be discussed in the following section.

According to VDE (2012), there are no CTMP plants in Germany, thus SGW and TMP are the primary mechanical wood production methods in focus. Figure 4 illustrates the SGW and TMP processes.

In SGW, small logs are ground on a rotating grindstone made from artificially bonded silicon carbide or aluminum oxide with the help of water (VDP, nd; Kramer et al., 2009). In TMP, wood chips are first steamed at high temperature, and then ground between two oppositely rotating grooved discs (VDP, nd; Kramer et al., 2009). The majority of wood pulp produced in Germany is produced by SGW (VDE, 2012).

The suitability of mechanical wood pulping for load shifting is viewed favourably by literature. Paulus and Borggrefe (2011) emphasises the ability of mechanical wood pulpers to ramp up and down within minutes, and the large capacity of pulp storage. VDE (2012) notes that SGW pulpers are able to operate on partial load in MW increments, and thus are tailor-made for load shifting.

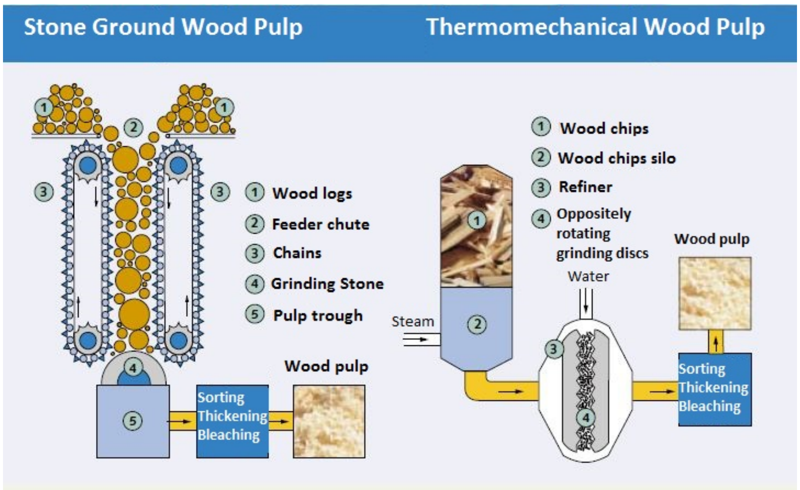

Figure 4: Mechanical wood pulp production methods (translated from VDP (nd))

Recycled Paper Pulping

Some studies (VDE, 2012; Paulus and Borggrefe, 2011; Müller and Möst, 2018) consider only mechanical wood pulping as suitable for load shifting; but other sources (Klobasa, 2007; Gils, 2015) also classify recycled pulp production as a load shifting application.

In recycled pulping, recycled paper is first softened with water, and then broken down using recycled paper pulpers, which operate similar to a kitchen mixer (Kramer et al., 2009). It is important to note here that throughout this work, the terms recycled paper pulp production or production capacity refers not to the mass of the effluent pulp-water mixture which exits the recycled paper pulper, but rather to the mass of the recycled paper input into the pulper.

Paper Production

From pulp (mechanical pulp, chemical pulp, recycled pulp, or a mix thereof), paper machines manufacture rolls of paper in a continuous conveyor process as depicted in Figure 5.

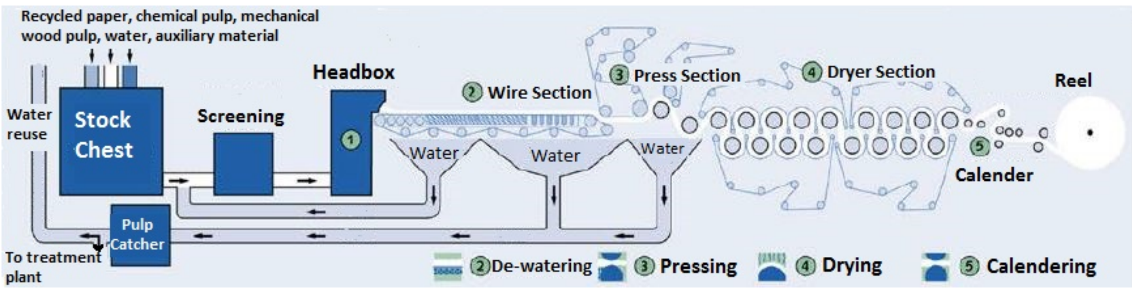

Figure 5: Paper production methods (translated from VDP (nd))

First, in the stock chest, a pulp, water, and additive mixture is made (VDP, nd). Either the pulp-water mix is pumped in directly from the pulp production section, or dry pulp is mixed with water (VDP, nd). Then the pulp mixture is distributed onto the paper machine conveyor where it undergoes successive drainage along a wire mesh, pressing between a series of hard rollers, drying along steam heated rollers, and smoothing in the calendar section, at which point the paper is complete and is rolled onto a steel core (VDP, nd).

Different kinds of paper are produced in Germany, the four main types being: graphic paper, paper for packaging purposes, paper for technical and special purposes, and hygienic paper (VDP, 2019c). Figure 6 shows the share of production of these different paper types, with packaging paper constituting the majority.

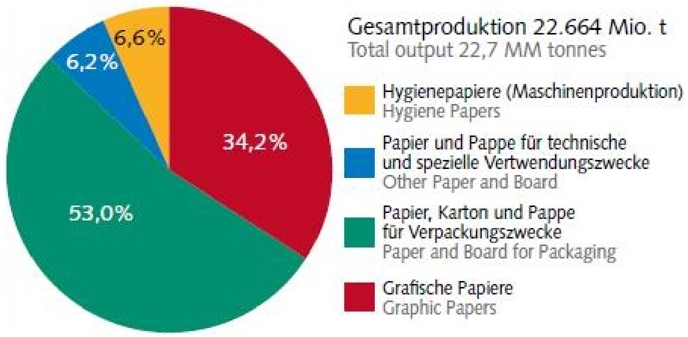

Figure 6: Share of main types of paper produced in Germany (VDP, 2019c)

Paper machine operation is less flexible in comparison to pulping machines (Klobasa, 2007; VDE, 2012). Plant shut-down and start-up requires 2 and 3 hours respectively, and the machines can only be shut down and started up block-wise (VDE, 2012).

Air Separation

Air separation is the extraction of nitrogen, oxygen, and argon from atmospheric air through a process of compression, cooling, and fractional distillation (Klobasa, 2007). According to Klobasa (2007), from personal communication with industry, air separation plants can be reduced to approximately 70% load.

2.2.3 Time Frame of Management

Four studies were reviewed which characterized time variables for industrial load shifting: Klobasa (2007), Gils (2015), Klobasa et al. (2013), and Müller and Möst (2018). Klobasa et al. (2013) is the study from which Gruber et al. (2014) obtains model inputs for the different load shifting applications. Klobasa et al. (2013) is referenced here because Gruber et al. (2014) does not utilize such time variables. Klobasa (2007) and Klobasa et al. (2013) report only one time parameter, which expresses the maximum duration of load shifting. In addition to the maximum duration of load shifting (referred to as t_{interf} by Gils (2015)), Müller and Möst (2018) and Gils (2015) use an additional time related parameter which defines the maximum time between the shifting and balancing of the load (referred to as $t_{shiftMax}$ by Gils (2015)). Figure 7 illustrates the difference between these two variables.

The use of these two different time parameters by Gils (2015) and Müller and Möst (2018) is a distinct difference from the model used in this work, which similar to Klobasa (2007), and Klobasa et al. (2013) considers only t_{interf}. Excluding $t_{shiftMax}$ means that the prior or subsequent balancing of a decrease in load is unrestricted.

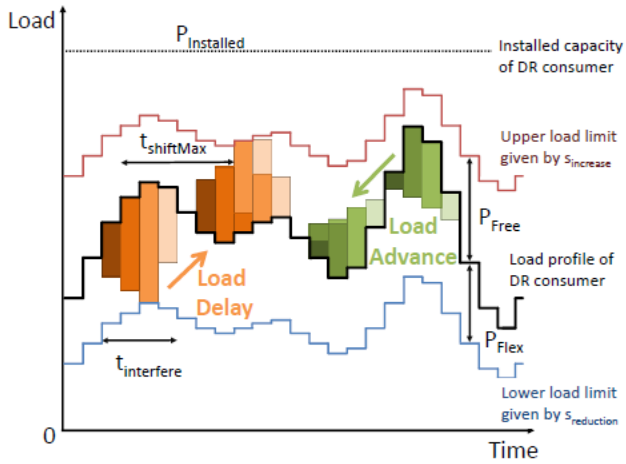

Figure 7: Time-resolved model load shifting parameters (Gils, 2015)

From this point forward in this report, the time parameter expressing the maximum duration of a load shifting intervention will be referred to as time frame of management (Δt); it must be noted that across literature the same parameter goes by a number of different names. Table 3 presents the different time frame of management values collected from literature. Under a particular application the different studies differ by only a maximum of one hour, but this one hour corresponds to a 33-50% difference which is considerable.

Table 3: Time frame of management (Δt) from literature [hours]

	Cement Mills	Mechanical Wood Pulp	Recycled Pulp	Paper Machines	Air Separation
Klobasa (2007)	3	2	-	-	4
Paulus and Borggrefe (2011)	-	-	-	-	-
VDE (2012)	-	-	-	-	-
Klobasa et al. (2013)	4	2	-	-	-
Gils (2015)	3	3	3	3	3
Müller and Möst (2018)	3	2	-	-	-

2.2.4 Flexible Component

The flexible component is a model input which although is not included in the original time-resolved load shifting model used in this work (refer to Section 3.1), is repeatedly found in literature. The flexible component expresses technical limitations on an application in increasing or decreasing its load. In the same way as Δt, this parameter appears under a variety of names across different studies. In this study the term flexible component (f) will be used.

Table 4 presents the different flexible component values obtained from literature. There was a key difference found between Gils (2015) and the three other studies reviewed which defined f: whereas Klobasa (2007), Gruber et al. (2014), and Müller and Möst (2018) analyze only negative power balancing potential, Gils (2015) analyzes both positive and negative power balancing potential. Thus, Klobasa (2007), Gruber et al. (2014), and Müller and Möst (2018) report a singular value for f, whereas Gils (2015) differentiates between positive and negative power flexibility by defining f_{inc} and f_{dec}. In Table 4, f_{inc} and f_{dec} is presented for Gils (2015), but for the other sources the value reported is their singular f, which is related to f_{dec} rather than f_{inc} from Gils (2015).

Table 4: Flexible component (f) from literature [%]

	Cement Mills		Mechanical Wood Pulp		Recycled Pulp		Paper Machines		Air Separation	
	f_{dec}	f_{inc}	f_{dec}	f_{inc}	f_{dec}	f_{inc}	f_{dec}	f_{inc}	f_{dec}	f_{inc}
Klobasa (2007)	50		100		-		-		30	
Paulus and Borggrefe (2011)	-		-		-		-		-	
VDE (2012)	-		-		-		-		-	
Gruber et al. (2014)	40		100		-		-		-	
Gils (2015)	50	100	0	100	0	100	70	100	60	100
Müller and Möst (2018)	100		100		-		-		-	

One problem in comparing values of the flexible component across the different studies is that the application of f in terms of calculating the negative power balancing potential by Gils (2015) is different than by Klobasa (2007), Gruber et al. (2014), and Müller and Möst (2018).

Gils (2015) application of f_{dec} is provided in Equations 2.3 of his dissertation. In Gils (2015), f_{dec} is a designated percentage of the installed capacity used to calculate a minimum allowable load. The negative power balancing potential is then calculated as the difference between the load and minimum load. And although not explicitly defined mathematically, Klobasa (2007), Gruber et al. (2014), and Müller and Möst (2018) state or imply that their f is defined as the flexible share of the total load, meaning that f is a designated percentage of the load.

As a result of Gils (2015) unique application of f_{dec}, a value of $f_{dec} = 0$ means that the minimum load for that application is in fact 0 MW, therefore corresponding to a flexible component of 100% by the definition of the other studies.

Gils (2015) defines f_{inc} as the percentage of free capacity available for load shifting, presented mathematically in Equation 2.4 of his dissertation.

Considering the different methodologies behind f utilized by the different studies, the figures from Gils (2015) compare relatively well with those from the other sources. Although they can not be precisely compared, assuming that the figures given by Gils (2015) are in reference to the maximum capacity, and the figures given by the other sources are in reference to the actual load, it would be expected that the f_{dec} figures from Gils (2015) would be somewhat greater than the other sources, but yet in a similar range because of the relatively high capacity utilization of industrial processes. The values seen in Table 4 agree with this assessment, with the exception of Müller and Möst (2018) in regards to cement mills, which reports 100% flexibility.

2.2.5 Load Profiles

Out of the studies reviewed, VDE (2012), Gils (2015), and Müller and Möst (2018) consider application specific load profiles. For all industrial processes other than cement mills, VDE (2012), Gils (2015), and Müller and Möst (2018) report a constant load profile.

The cement mill load profiles used or reported by VDE (2012), Gils (2015), and Müller and Möst (2018) all vary from each other in certain ways, but generally feature decreased load during the daytime hours on weekdays, and decreased load during a period in the winter. According to VDE (2012) cement mills shut down during the day on weekdays to avoid peak period electricity prices, and shut down for approximately six weeks during the winter (December-March) due to halting of construction activities. However, the timing of the winter shut-down is difficult to predict because cement milling is governed by the activities of the construction industry, and the activities of the construction industry is governed by temperature (VDE, 2012). Müller and Möst (2018) model this behavior by dictating that if the outdoor temperature is equal to or less than zero degrees Celsius, the cement milling load falls to zero. Gils (2015) assumes that the cement milling load reduces by 20% during the winter, however there is no clear definition of what period of time is meant by winter, and also no source given behind the assumptions. The methodology of Müller and Möst (2018) agrees with the information provided by VDE (2012) significantly better than Gils (2015).

The load variation of cement mills during the weekday daytime hours is a result of present day load shifting behaviours to avoid high electricity prices (VDE, 2012). In the future, if the tariff system would change, the operation of cement mills would change accordingly (VDE, 2012).

2.2.6 Annual Energy Demand

As previously mentioned in Section 1.3, there are two main methods of estimating application specific industrial demand found in the reviewed literature: production data and specific energy demand, and industry surveys. This section discusses the use of production data and specific energy demand, as surveys are not utilized in this work. The methodology of calculating annual energy demand from production data is used both in the plant specific characterization method, and one of the alternative methods tested in this work. In addition, a top down approach used by Beer (2012) to estimate industry branch annual energy demand will be presented here because it is used in the development of the alternative methods of estimating application specific annual energy, presented in Section 3.2.4. Note that industry branches are significantly broader industry classifications than the industrial load shifting applications considered by the other reviewed literature, and which are used in this work.

Two slightly different calculation methods using production data and specific energy demand were found: one used by Gils (2015), and the other used by the remainder of the reviewed sources which did not rely on surveys. The distinction between these two methods is a result of the distinction between production capacity, and actual production. Production capacity is the maximum quantity of product that a plant is able to produce if running at full operational capacity. Actual production is typically less than production capacity and expresses the real quantity of product produced by a plant in any given year. Equation 1 shows the method used by Gils (2015) with production capacity, and Equation 2 shows the method used by Klobasa (2007), Gruber et al. (2014), and Müller and Möst (2018) using actual production.

$$e_y = p_{yc} * e_i * s_{util} \tag{1}$$

Where:
e_y = annual energy demand [MWh]
p_{yc} = annual production capacity [tonnes]
e_i = specific energy demand [kWh/tonne]
s_{util} = capacity utilization [%]

$$e_y = p_y * e_i \tag{2}$$

Where:
p_y = annual production [tonnes]

In both methods, specific energy demand is required. Table 5 presents the specific energy figures collected from the reviewed literature.

Table 5: Specific energy demand (e_i) from literature [kWh/tonne]

	Cement Mills	SWG Pulp	TMP Pulp	Recycled Pulp	Paper Machines	Oxygen	Nitrogen	Argon
Klobasa (2007)	45	2090	2640	200-300	325-550	-	-	-
Paulus and Borggrefe (2011)	100	1500		-	-	-	-	-
VDE (2012)	30-60	-	-	-	892	-	-	-
Gruber et al. (2014)	45	2090	2640	-	-	-	-	-
Gils (2015)	110	1500		250	425	238	160	224
Müller and Möst (2018)	42	2000		-	-	-	-	-

The specific energy demand for cement milling varies considerably across different sources. Specifically, there are several studies reporting a specific energy demand of approximately 100 kWh/tonne, with the other studies reporting a specific energy demand of approximately 45 kWh/tonne. The reason behind this significant difference was investigated further, and it was found that it is a result of total production chain energy demand versus process specific energy demand. According to VDZ (2019a), the total specific energy demand for cement is 110.9 kWh/tonne, but only 46% of this energy (51 kWh/tonne) is used for cement milling.

In regards to mechanical wood pulp production, Klobasa (2007) and Gruber et al. (2014) both clearly distinguish between SGW and TMP pulping, and report the exact same specific energy for the two different applications. Paulus and Borggrefe (2011), Gils (2015), and Müller and Möst (2018) refer to mechanical wood pulping in general and it is not clear whether they are referring to SGW pulping, TMP pulping, or both.

In regards to paper machines, from the context of VDE (2012), the reported 892 kWh/tonne figure is for the entire paper production process chain rather than paper machines in isolation, therefore the figures given by Klobasa (2007) and Gils (2015) are more accurate for the application of this work.

The s_{util} values gathered from the reviewed literature are shown in Table 6. Although the reviewed sources other than Gils (2015) do not calculate annual energy demand using s_{util}, capacity utilization is highly reported and used for other purposes such as calculating maximum capacity (refer to the following section), to calculate average load from maximum capacity, or simply as general information on the application. Some of the reviewed sources report full load hours rather than percent utilization; these figures were converted into percent utilization based on the number of hours in a 365 day year.

Table 6: Capacity utilization (s_{util}) from literature [%]

	Cement Mills	Mechanical Wood Pulp	Recycled Pulp	Paper Machines	Air Separation
Klobasa (2007)	-	-	-	85	-
Paulus and Borggrefe (2011)	80	80	-	-	-
VDE (2012)	74	78	-	86	-
Gruber et al. (2014)	63	85	-	-	-
Gils (2015)	80	80	80	90	80
Müller and Möst (2018)	60	64	-	-	-

The top-down approach used by Beer (2012) is outlined in Figure 8. In this method, NUTS-0 Wirtschaftszweige 2008 (WZ08)[3] branch energy demand data from Statistisches Bundesamt is disaggregated to the NUTS-4 level using employment data also from Statistisches Bundesamt. An additional important feature of the method used by Beer (2012) is that the electricity

[3] WZ08 is the abbreviation for 'classification of economic activities, 2008 edition' (Klassifikation der Wirtschaftszweige, Ausgabe 2008). WZ08 is the current classification system for economic activities used in Germany. More information can be found at Statistisches Bundesamt (2019b).

consumption per industry branch includes both energy drawn from the grid, as well as energy consumed from industry private power generators.

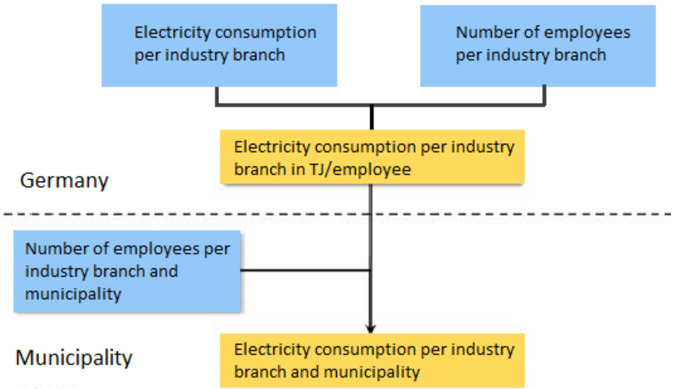

Figure 8: Top-down regional WZ08 industry branch annual energy demand estimation method (translated from Beer (2012))

2.2.7 Maximum Capacity

There are several different ways of determining maximum capacity observed in the studies reviewed. Paulus and Borggrefe (2011) and VDE (2012) report NUTS-0 application specific maximum capacity extrapolated from industry surveys. Klobasa (2007) and Gruber et al. (2014) do not analyse maximum capacity, but rather focus on average load and shiftable load. Gils (2015) and Müller and Möst (2018) calculate maximum capacity by dividing the previously calculated annual energy demand by a time figure, but their calculations differ slightly.

Gils (2015) calculates maximum capacity using Equation 3, which assumes that production capacity is the quantity of product that can be produced if the plants are running at 100% capacity at all time with the exception of the period of annual revision- a period of shut-down necessary for maintenance.

$$\Lambda = \frac{e_y}{8760 * (1 - f_{rev}) * s_{util}} \tag{3}$$

Where:
Λ = maximum capacity [MW]
e_y = annual energy demand [MWh]
f_{rev} = period of annual revision [%]
s_{util} = capacity utilization [%]

Müller and Möst (2018) calculate maximum capacity using Equation 4 and full load hours.

$$\Lambda = \frac{e_y}{n_{flh}} \tag{4}$$

Where:
n_{flh} = number of full load hours [hours]

Note that Equations 3 and 4 are equivalent if one excludes f_{rev} from Equation 3, and considers that $n_{flh} = 8760 * s_{util}$.

2.3 Industrial Process Heat Load Shifting

Final energy demand in the industrial sector is dominated by heat generation (Gruber et al., 2015; Gils, 2015; Naegler et al., 2015). Of the total industrial heat demand, the majority (86%) is used for the provision of process heat (PH), while 14% is for the provision of space heating and hot water (Gruber et al., 2015). As industrial heat demand is monopolized by PH, and space heating and hot water also falls under the classification of cross-sectional technologies which are excluded in this work, this work will investigate only industrial PH.

Process heating applications can be divided into two categories: that which is currently provided by electricity (electrothermal applications), and that which is currently provided by fuel (fuel-based applications) (Gruber et al., 2015). As of 2012, only 8.7% of industrial PH is provided by electricity (Gruber et al., 2015). There is a diverse range of electrothermal PH applications, however it is important to note that not all of them are flexible (Gruber et al., 2015).

A select few studies on the topic of industrial heat demand were reviewed: Gruber et al. (2015), Gils (2015), and Naegler et al. (2015). Gruber et al. (2015) estimates the flexibility potential of electrothermal applications, and the electrification potential of fuel-based applications in Germany. Gils (2015) analyses industrial heat demand with the context of estimating the potential of supplying it with CHP plants across Europe, and Naegler et al. (2015) estimates the industrial heat demand for European countries.

A common topic of analysis among these three studies is the focus on categorization of industrial heat demand by temperature, which is essential for determining what technologies are applicable for supplying which quantities of industrial heat demand (Gruber et al., 2015; Gils, 2015; Naegler et al., 2015).

The DR potential of select electrothermal applications have already been evaluated by a number of previous studies. Applications such as electrolytic aluminum production, chloralkali processes, and electric arc furnaces are standard DR applications considered in literature, but are typically regarded to be load shedding rather than load shifting applications (Klobasa, 2007; Paulus and Borggrefe, 2011; VDE, 2012; Gils, 2015; Gruber et al., 2014, 2015; Müller and Möst, 2018). However, there may be other electrothermal applications which are suitable for load shifting, which have not yet been investigated; Gruber et al. (2015) identifies several such possible applications.

In regards to currently fuel-based PH applications, according to Gruber et al. (2015), virtually all applications can be electrified in theory. The exceptions would be applications where the fuel also serves as a raw material, or for which construction of a new plant would be required (Gruber et al., 2015). Gruber et al. (2015) however, does not investigate the flexibility of such electrified PH applications. The most apparent mechanism of flexibilization is decoupling of the heat generation and heat demand using a thermal energy storage, which already exists for some applications (Gils, 2015; Gruber et al., 2015). According to Gruber et al. (2015), PH is generally supplied indirectly via hot water or steam networks for applications up to 240 °C, in which range electrical heating technologies such as heat pumps, electric boilers, or electrode boilers can easily be integrated. Gils (2015) considers applications up to 500 °C as suitable for CHP, which implicitly includes heat storage. Electrical heat generation and storage at even higher temperatures is possible; according to Sterner and Stadler (2014) thermal storage up to 1000 °C is achievable, and power-to-heat with storage for industry application at 1000 °C has been piloted (Meyer, 2019). There is also the theoretical possibility of using more basic, lower temperature technologies such as low temperature thermal energy storage with electric boilers or heat pumps to generate a base temperature, with fuel-based heat generation technologies to increase the temperature as required for higher temperature applications in following.

With the exception of the select electrothermal applications previously mentioned (electrolytic aluminum production, chloralkali processes, and electric arc furnaces), the reviewed studies do not estimate the DR potential of PH applications in the same manner as the industrial process applications discussed in Section 2.2. Because PH load shifting pertains mainly to systems which are not currently installed, but will require electrification in the future, there are significant knowledge gaps. In regards to model inputs, Gils (2015) provides methods for estimating annual energy demand, maximum capacity, and provides load profiles for industrial PH, but no proposed values for Δt, or f could be found in the reviewed literature. The time frame of management (Δt) would theoretically be governed by the size of the thermal energy storage, and the PH load that it needs to supply, but could also influenced by other logistical constraints. The flexible component f represents the flexible share of PH demand, but it is difficult to estimate the flexible shares that may be achievable in the future due to the wide array of PH temperature ranges and applications, heating and heat storage technologies, as well the financial feasibility of such technologies.

In the face of these uncertainties and knowledge gaps, this work presents a short, preliminary investigation into NUTS-3 PH load shifting potential. NUTS-3 regionalization of industrial branch PH annual energy demand is be performed, as well as a comparison as to which Δt and f result in PH load shifting potential in the approximate range of what is estimated for the industrial processes.

3 Methodology

This section provides a detailed description of the methods used in this work. Section 3.1 describes the previously developed time-resolved DR model framework by Kleinhans (2014) that has been adapted for this work. In the following Section 3.2, the most appropriate values or methods of generating the required model inputs are selected based on the literature reviewed in Section 2. The details of the plant specific characterization method, and the three alternative methods developed for use with easily accessible data are reviewed in Section 3.2.4. The methodology used in estimating industrial PH load shifting potential, and future projections of the potential for industrial processes are presented in Section 3.3 and 3.4 respectively.

3.1 Time-Resolved Demand Response Model

The time-resolved DR model developed by Kleinhans (2014) is a model of intermediate complexity which is intended to enable large scale sector specific profiles to be straightforwardly taken into account, and be suitable for integration into large scale simulations. Load shifting applications are modeled as an equivalent energy storage device, also referred to by Kleinhans (2014) as storage equivalent energy buffers. Similar to conventional energy storage devices such as batteries, the storage equivalent energy buffer has a storage capacity [MWh], and maximum charging and discharging power [MW]. However, unlike conventional energy storage devices, the storage capacity and charging and discharging power of load shifting storage equivalent energy buffers have an explicit time dependence. In contrast to conventional energy storage devices, the primary use of load shifting devices is not energy storage, but rather to fulfill an unrelated energy service for the user, such as producing goods. The time dependence of the storage equivalent energy buffers is due to the time dependent availability of the loads for demand modification as a result of the load schedule.

Three key parameters are required as input for the time-resolved DR model:

1. Scheduled load time series ($L(t)$). This is the load curve for a given application, without any load shifting modifications.
2. Time frame of management (Δt). This is the maximum duration of negative balancing power DR intervention; in other words, the maximum duration of time that the load can be decreased to the minimum possible load.
3. Maximum capacity (Λ). This is the maximum realizable load for a given application.

These three inputs are then used to calculate the time dependent maximum and minimum power and energy of the storage equivalent energy buffer for a particular application. The maximum and minimum power and energy time series forms boundaries that the storage equivalent energy buffer power and energy must lie within; these boundaries and the space they enclose are referred to as envelopes. The power and energy envelopes are expressed mathematically by Equation 5 and Equation 6 respectively.

The model views any increase in load from the scheduled load $L(t)$ as charging power to the storage equivalent energy buffer. Consequently, as expressed by Equation 5a, the maximum charging rate is achieved when the load is increased to the maximum capacity, and is equal to the difference between the maximum capacity and scheduled load.

Conversely, any decrease in load is analagous to discharging the storage equivalent energy buffer. Thus, as expressed in Equation 5b, the maximum discharging rate would be achieved by completely shutting down the load, and would be equivalent to the scheduled load. A negative sign is added to conform to the convention of power delivery as negative power.

As for the energy envelope equations, Equation 6a expresses the maximum quantity of energy that is possible to have stored on the storage equivalent energy buffer at time t in charging mode; likewise, Equation 6b expresses the maximum quantity of energy that is possible to have discharged from the energy buffer at time t in discharging mode.

$E_{max}(t)$ corresponds to the condition of preponing all available load within the time window Δt. With a reference of time t, the load from t to $t + \Delta t$ is shifted to an earlier time, meaning the load prior to t is increased in some manner which balances the energy contained within the preponed segment of load. Thus, by time t, the storage equivalent energy buffer has been charged with a quantity of energy equal to the integral of the load from t to $t + \Delta t$.

In the same way, $E_{min}(t)$ corresponds to the condition of postponing all of the available load within a time window of duration Δt. From the reference of time t, the load from time $t - \Delta t$ to t is shifted to a later time, meaning that the load prior to t is decreased to the minimum possible load. Thus by time t, the energy buffer has discharged a quantity of energy equal to the integral of shifted load over the time from $t - \Delta t$ to t.

$$P_{max}(t) = \Lambda - L(t) \tag{5a}$$

$$P_{min}(t) = -L(t) \tag{5b}$$

$$E_{max}(t) = -\int_{t}^{t+\Delta t} P_{min}(t)\ dt \tag{6a}$$

$$E_{min}(t) = \int_{t-\Delta t}^{t} P_{min}(t)\ dt \tag{6b}$$

As the power and energy envelope equations define the maximum positive and negative balancing power, and the volumes of chargeable and dischargeable energy, Equations 5 and 6 define the load shifting potential of a given application. However, Equation 5 assumes complete load flexibility. As first mentioned in Section 1.4, in this work an additional input will be integrated into the model framework - the flexible component f [%]- to incorporate a basic measure of technical limitations. From the literature reviewed in Section 2.2.4, the flexible component methodology from Gils (2015) is selected for adaptation in this work because it is the only reviewed source which mathematically defines the use of f, and distinguishes between the ability of an application to increase or decrease its load using the parameters f_{inc} and f_{dec}. Refer back to Section 2.2.4 for further information regarding f_{inc} and f_{dec}.

The modifications required to the power envelope equations are apparent from Equation 2.3 and 2.4 in Gils (2015). Equation 7 shows the modified power envelope equations (modified from Kleinhans (2014) based on Gils (2015)). In Equation 7, if the scheduled load is less than the minimum load calculated from $\Lambda * f_{dec}$, then it is assumed that the load can not be allowed to decrease further, thus $P_{min}(t) = 0$. The energy envelope equations (Equation 6) remains unmodified.

$$P_{max}(t) = (\Lambda - L(t))f_{inc} \tag{7a}$$

$$P_{min}(t) = \begin{cases} -(L(t) - \Lambda * f_{dec}) & L(t) \geq \Lambda * f_{dec} \\ 0 & L(t) < \Lambda * f_{dec} \end{cases} \tag{7b}$$

Figure 9 illustrates the determination of the power and energy envelopes visually, with the simple case of constant scheduled load.

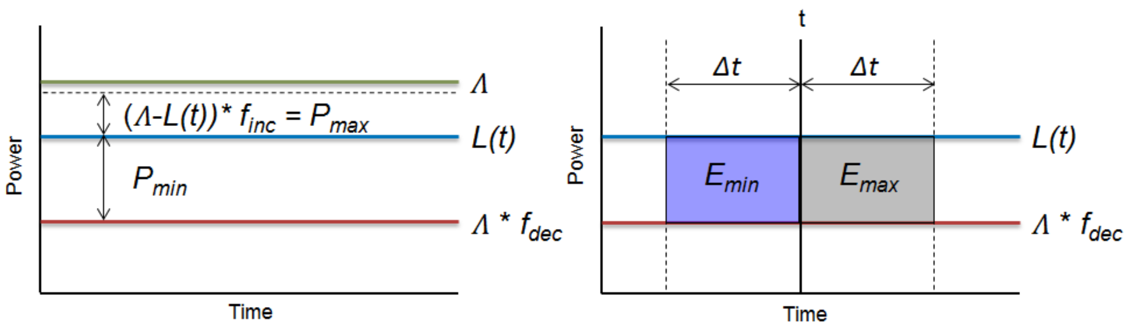

Figure 9: Time-resolved load shifting model for determination of load shifting potential

3.2 Industrial Process Load Shifting

Table 7 consolidates the selected numerical model inputs which are constant across all NUTS-3 regions. Time frame of management (Δt), and flexible component (f_{inc} and f_{dec}) are direct model inputs, used according to Equations 6 and 7. Specific energy demand (e_i) and capacity utilization (s_{util}) are indirect model inputs, used to calculate annual energy (e_y) from production data for scaling the load profile to produce $L(t)$, and to calculate maximum capacity (Λ).

The selection of these model inputs is covered in Sections 3.2.1, 3.2.2, and 3.2.4. Section 3.2.3 discusses the selection of and use of load profiles, and in addition to the selection of e_i and s_{util}, Section 3.2.4 also covers the methodology of the different methods for calculation and regionalization of annual energy demand: the plant specific characterization method adapted from literature, and three self-developed alternative methods suitable for use with easily accessible data.

Table 7: Selected model inputs from literature

	Δt [hrs]	f_{dec} [%]	f_{inc} [%]	e_i [kWh/tonne]	s_{util} [%]
Cement Mills	4	50	100	51	70
Mechanical Wood Pulp	2	0	100	1090	77
Recycled Pulp	3	0	100	220	80
Graphic Paper Machine	3	70	100	417	93
Packing Paper Machine	3	70	100	131	93
Hygiene Paper Machine	3	70	100	884	93
Technical Paper Machine	3	70	100	212	93
Oxygen Separation	4	60	100	238	80
Nitrogen Separation	4	60	100	160	80
Argon Separation	4	60	100	224	80

3.2.1 Time Frame of Management

Refer to Table 3 for the complete overview of time frame of management values collected from literature.

In regards to recycled paper pulpers and paper machines, because only one source from the reviewed studies reported any values for Δt, Gils (2015) value of 3 hrs for both is taken. For cement mills, Klobasa (2007), Gils (2015), and Müller and Möst (2018) all use a Δt of 3 hours; however both Gils (2015) and Müller and Möst (2018) take Δt directly from Klobasa (2007). Klobasa et al. (2013) is a more recent study than Klobasa (2007), and the data provided is based on an industry survey. Thus, Klobasa et al. (2013) is deemed to be the most representative source for Δt for cement plants, with 4 hrs.

In terms of mechanical wood pulpers, all sources with the exception of Gils (2015) are in agreement with 2 hrs. The reason behind the deviation of Gils (2015) is unknown, but it can be noted that Gils (2015) selected 3 hrs as Δt for all industrial load shifting applications, perhaps as a simplification. For these reasons, 2 hrs is selected as Δt for mechanical wood pulpers.

Klobasa (2007) and Gils (2015) are the only two studies which report Δt for air separation plants, with 4 hours and 3 hours respectively. Because the data provided from Gils (2015) for air separation plants is cited to Klobasa (2007), and no reason for the deviation is given, the value of 4 hrs given by Klobasa (2007) is selected for use in this work.

3.2.2 Flexible Component

The f values from Gils (2015) are selected for use in this work because the methodology used by Gils (2015) is unique, and thus if adapting the methodology from Gils (2015), only his values are truly applicable for use. In addition, as discussed in Section 2.2.4, the values used by Gils (2015) compare reasonably well with other sources.

3.2.3 Load Profiles

In accordance with VDE (2012), Gils (2015), and Müller and Möst (2018), a constant load profile is used for all industrial processes with the exception of cement mills. For the cement mill load profile the daily variation featured by VDE (2012), Gils (2015), and Müller and Möst (2018) will be disregarded. As discussed in Section 2.2.5, the load variation of cement mills during the weekday hours is present day load shifting to avoid peak period electricity prices. As such, if the daily variation is included in the load profile it would not be representative of $L(t)$ (load profile without any load shifting modifications), and would not reflect the true flexibility potential of cement mills.

In contrast, the winter shut-down must be accounted for in the cement mill load profile. In this work, a methodology similar to that used by Müller and Möst (2018) is used for modelling the winter shut-down. As discussed in Section 2.2.5, in Müller and Möst (2018), cement mills are shut down to zero load if the temperature is less than or equal to 0 °C, and VDE (2012) reports that cement mills in Germany shut down for a period of approximately six weeks as a result of low temperatures preventing construction work. As construction activities are governed by local temperatures, and cement mills typically deliver cement on a local basis due to high shipping costs (VDZ, 2019a), the winter shut down of cement mills is presumed to be regionally dependent.

To model the regional and temperature dependence on the operation of cement mills, a dataset of NUTS-3 average monthly temperature, previously developed by Heitkötter et al. (2019) using data from Institut für Wohnen und Umwelt (2018)[4] is used. Each NUTS-3 region is assigned the data from the weather station closest to the NUTS-3 region's geometrical center point, and the monthly average temperature is averaged over all available years of operation of the weather station (since approximately 1970). With using monthly temperature data, if the monthly average temperature in a particular NUTS-3 regions is less than or equal to the threshold temperature, the cement mills within that NUTS-3 region shut down to zero load for that month.

As a result of using regional temperature data, the cement plants in different NUTS-3 regions are closed for different periods of time, with some not being shut down at all due to regionally warm temperatures. With a threshold temperature of 0°C, it was found that the NUTS-0 average duration of winter shut down was 1.7 weeks, which is significantly lower than the 6 weeks reported by VDE (2012). To more closely model the industry information given by VDE (2012), the threshold temperature was increased to 1.4°C, which results in an NUTS-0 average winter shut down of 5.6 weeks.

3.2.4 Annual Energy Demand

As previously mentioned in Section 1.4, annual energy demand is a key parameter in this work because it is the basis of regionalization of the load shifting potentials; the determination of NUTS-3 scheduled load ($L(t)$) and maximum capacity (Λ) is derived from NUTS-3 annual energy demand.

Four different methods of estimating NUTS-3 annual energy demand are conducted in this work. The first method is the plant specific characterization method, which as mentioned in Section 1.3 is the method found in the reviewed literature used to estimate NUTS-3 annual energy demand for industrial processes. However, the methodology for this method in Gils (2015), Gruber et al. (2014), and FfE (2016) is only loosely defined. In this work, the general concept of gathering site specific production information using publicly accessible sources is adopted, but the methodology is elaborated on and extended as necessary. Because the plant specific characterization method involves highly detailed site specific data, it is regarded as the inherently most reliable method out of the four methods conducted, and is used as the control method to compare the three other methods against.

The aim of the three other methods is to estimate NUTS-3 annual energy demand for industrial processes using easily accessible data from online statistical databanks and industry associa-

[4]The data from Institut für Wohnen und Umwelt (2018) is originally obtained from the German Meteorological Service (Deutscher Wetterdienst)

tions, or in other terms to replicate the results of the plant specific characterization method as closely as possible without the need for time consuming data gathering. These three methods to be tested are self-developed, but draw from general regionalized energy demand estimation concepts relying on statistical data found in literature, such as in Gils (2015), Beer (2012), and Wittekind (2019). The three methods are termed: the allocation of NUTS-0 production method, the allocation of NUTS-0 energy demand method, and the NUTS-3 total industrial energy demand method. The allocation of NUTS-0 energy demand method in particular draws from methodology used by Beer (2012).

In this subsection, the selection of specific electrical energy demand and capacity utilization will be addressed first. These two parameters are necessary for estimating annual energy demand using the plant specific characterization method, and the allocation of NUTS-0 production method. Then the methodology of the plant specific characterization method used in this work, as well as the methodology behind between the three alternative methods will be described.

Specific Electrical Energy Demand and Capacity Utilization

Refer to Tables 5 and 6 for the complete overview of e_i and s_{util} values found in the reviewed literature.

For cement milling, the specific energy of 51 kWh/tonne (VDZ, 2019a) is selected, as it is obtained directly from the Association of German Cement Works (Verein Deutscher Zementwerke) (VDZ) and therefore is expected to be the most accurate source for cement plants in Germany. In addition, it is also a very recent source. In regards to utilization, the reviewed literature reported a distributed range of values from 80% to 60%. None of these individual sources could be credited or discredited above the others, therefore the midpoint value of the literature range (70%) is adopted.

In regards to mechanical wood pulping, recycled paper pulping, and paper machines, further investigation into specific energy demand was needed due to: (1) discrepancies between different sources for mechanical wood pulping, and a lack of clarity on whether figures provided pertain to SGW, TMP, or a combination of the two, and (2) to update the specific energy figures to the best extent possible, as it was observed that the sources behind the majority of the figures provided by the reviewed literature are rather outdated.

For mechanical wood pulping, it was found that available production data sources unfortunately do not differentiate between SGW and TMP pulp, therefore utilizing differentiated specific energy demand figures is not possible. As it has been reported that the majority of wood pulp produced in Germany is SGW (VDE, 2012), it will be assumed in this work that all mechanical wood pulping operations are SGW. The most recent source for SGW specific energy demand that was found was an updated edition of the source cited by Gils (2015): Taschenbuch der Papiertechnik by Jürgen Blechschmidt. According to Blechschmidt (2013), typical specific energy demand for SGW is 900-1500 kWh/tonne oven dry wood pulp, the midpoint within this range being 1200 kWh/tonne. This oven dry (100% dry) figure must be adjusted for moisture content, because the production data provided by Statistisches Bundesamt is in the unit of 90% dry pulp, and the site specific production data found is in the unit of air dry pulp, which is also considered to be 90% dry (Briggs, 1994). Adjusting for 10% moisture content results in a specific energy demand of 1090 kWh/tonne.

VDP (2019c) provides national mechanical wood pulp capacity (1 061 000 tonnes) and production (813 127 tonnes) data for 2018, from which a capacity utilization of 77% is calculated. As the Association of German Paper Factories (Verband Deutscher Papierfabriken) (VDP) is the national industrial association for paper producers and thus is expected to have the most accurate information, 77% utilization is adopted for this work. This figure from VDP is quite close to the figure of 80% reported by 3 of the 5 reviewed literature sources.

In regards to recycled paper pulping, the specific energy demand is dependent on whether the operations include deinking processes or not (Blechschmidt, 2013). For plants without deinking, the electricity requirement can expected to be 110 kWh/tonne; the electricity requirement for plants with deinking is higher, at 330 kWh/tonne (Blechschmidt, 2013). The midpoint between 110 kWh/tonne and 330 kWh/tonne (220 kWh/tonne) is taken to be the most representative figure for the purposes of this work, because as a rule it is not possible to determine whether a plant has deinking operations or not from the information used in this work. The specific energy demand of 220 kWh/tonne agrees well with that reported by Gils (2015) (which is derived from a 2006 source), and Klobasa (2007), but is slightly lower, as might be expected for more modern plants. The utilization of 80% from Gils (2015) is selected because it is the only reported value in the literature reviewed, and it agrees with the utilization of mechanical wood pulpers, which is reasonable as they both provide the same function within a paper mill of producing pulp to feed into the paper machines.

Vogt et al. (2008) provides average paper machine specific electrical energy demands for the four main categories of paper, derived from an industry survey: graphic paper (417 kWh/tonne), packaging paper (131 kWh/tonne), hygiene paper (884 kWh/tonne), and technical paper (212 kWh/tonne). These paper type specific energy demands will be used in this work over the figures used in the reviewed literature because the values used by Klobasa (2007) and Gils (2015) originate from an older 2001 source, and from Vogt et al. (2008) it is apparent that there is a significant difference in annual energy demand between the different types of produced paper that the reviewed literature does not take into account. Paper type is relatively accessible information to obtain, on both a plant specific basis as well as from production data provided by Statistisches Bundesamt and VDP. Utilizing the paper type specific e_i from Vogt et al. (2008) should result in more accurate estimations of annual energy demand, especially on a NUTS-3 level using the plant specific characterization method. For paper machine utilization, the reported capacity utilization for 2018 by VDP will be used, at 93% (VDP, 2019c). This figure from VDP is slightly higher than the highest paper mill utilization reported in the reviewed literature, which was 90% by Gils (2015).

For air separation of oxygen, nitrogen, and argon, the specific energies of 238, 160, and 224 kWh/tonne, respectively are selected (Gils (2015), from Häring (2008)), as they are the only figures for air separation provided by the reviewed literature, and are also from a relatively recent and reputable source. The utilization of 80% is also adopted from Gils (2015).

Plant Specific Characterization Method

In the plant specific characterization method, individual industrial plants are identified, and their locations and production or production capacities are characterized. To identify the different plants and their locations, German national industry associations are used: for example VDZ for the cement industry, and VDP for the pulp and paper industry. These national associations have publicly accessible registers of member plants online, including plant addresses. The list of cement plants is taken from the register on the VDZ website (VDZ, 2019c).

For paper mills, there are several sources for lists of plants accessible online through VDP: the A-Z register (VDP, 2019a), the headquarters and mills map (VDP, 2017), and the annual VDP performance report (Leistungsbericht) (VDP, 2019c). The performance report is considered to be the most recent and authoritative source on member plants, however, it also includes several locations which are simply head offices with no production equipment. These administrative offices are identified and excluded from the performance report list using the headquarters and mills map. The list of mechanical wood pulping operations is obtained from the VDP product specific online registry (VDP, 2019b), by selecting for wood pulp producer (Holzstofferzeuger). The list of recycled paper pulping operations is obtained by extracting those plants from the A-Z register which have recycled paper processor (Altpapierverarbeiter) listed as an attribute.

It should be noted that it is possible that these registers do not include all of the plants in Germany, as some plants may not be members of the association. For example, according to VDZ (2019c), there are 53 cement plants in Germany, with 46 of them being VDZ members. However, the registers from the national associations are considered to be sufficiently exhaustive. In addition, on occasion a plant listed by the corresponding industry association is found in later research to have closed or to have changed ownership. In these cases, appropriate modifications are made to the list of plants. If the plant appears to have shut down, with no news of resale of the plant, it is excluded from the list of plants; however, it is possible that these plants may resume operations in the future.

After the list of plant names and locations is extracted from the national industry associations, the individual plant production or production capacity is searched for in online, publicly accessible sources. The preferred source for production and production capacity data is the company website. If the company does not report the production or production capacity of the plant, then secondary sources are reviewed. Useful secondary sources include online news reports, industry magazines, and local government documents. Either production, or production capacity can be reported by the various sources; if available, production capacity is preferred because production can change from year to year whereas production capacity is constant as long as the plant is not modified. Whether the data gathered represents production or production capacity must be noted for each plant, as from Section 3.2.4, this affects the calculation of annual energy demand.

For several cement plants, the only available production or production capacity data is that of cement clinker. The quantity of material ground by the cement mill itself would be expected to be slightly more than the quantity of cement clinker produced, because as from Section 2.2.2, cement is comprised of cement clinker and supplementary materials such as gypsum. The ratio of cement clinker to other materials depends on the type of the cement (VDZ, 2019b). To convert cement clinker production into cement production the type of cement the plant produced must be determined, as well as if the supplementary materials are ground along with the cement clinker or if they are added afterwards. In this work, the few plants for which only cement clinker production or production capacity was available were identified to be Portland cement producers. According to VDZ (2019b), Portland cement is 95% clinker, and up to 5% supplementary materials. This supplementary material is typically gypsum, which is interground with the cement clinker (Ingham, 2013). Thus, the quantity of cement clinker is converted into quantity of ground cement material by: $cement = clinker/0.95$.

In addition, several other cement plants are not cement clinker grinding mills, but rather blast furnace slag grinding mills. Slag is a by-product of the iron production process, and ground slag is typically used to replace a portion of Portland cement (SCA, 2019). In the cases where only the quantity of slag ground is available, it is assumed that the plant grinds only slag, hence no modification to the quantity is made.

In regards to paper mills, it was found that the majority of online sources report the production or production capacity of paper production, but not that of the wood pulping or recycled paper pulping machines. This is because the paper is the final product of the plant, whereas the wood and recycled paper pulpers are upstream processes producing the input material for the paper machines, and thus are of less importance to report on.

For the majority of paper mills, the production or production capacity of paper is able to be identified. If the paper production or production capacity cannot be identified, it is estimated using the total production or production capacity of the company and the plant specific employees if available (for companies with multiple locations), or using the number of employees of the plant in combination with the employee specific production of a similar plant type for which both the production and employee data are available.

The production capacity data for mechanical wood pulping operations in Germany is obtained from a document published by the Renewable Raw Materials Specialist Agency (Fachagentur Nachwachsende Rohstoffe), an associate organization of the German Federal Ministry of Food and Agriculture. A similar source for the production capacity of recycled paper pulping operations was unfortunately unable to be identified. Due to the lack of available data for recycled paper pulping, the production or production capacity has to be estimated for the majority of plants.

A small number of paper mills provide production or production capacity for their recycled paper operations, which is taken as the preferred data source when available. If the recycled paper production or production capacity is not directly available, recycled paper content [%] of the produced paper reported by the company or by secondary sources is used in combination with the previously determined paper production of the plant to estimate the quantity of recycled paper pulped by the plant. If neither the recycled paper production capacity or the recycled paper content for the plant is available, the German national average ratio of recycled paper input to produced paper, obtained from VDP is used to estimate the recycled paper production. VDP (2019c) reports the national average ratio of recycled paper to produced paper for the four main types of paper, and five subcategories. The most appropriate classification for each plant is identified, and the corresponding ratio applied accordingly.

When using recycled paper content data, a small modification is made because the recycled paper content represents the percentage of recycled paper pulp in the finished paper product, but not quantity of input recycled paper to the pulpers. This is because a certain percentage of the input recycled paper is lost in the pulping process, due to fibre degradation or other mechanisms (VDP, 2015). From VDP (2019c), the highest ratio of recycled paper to produced paper is that for newspaper (Zeitungsdruckpapier), at 113%. From this it is assumed that newspaper has a recycled paper content of approximately 100% in Germany, and the extra 13% represents recycled paper that is pulped, but does not make it into the final product. Based on this information from VDP, if it is reported that the recycled paper content of the paper produced by a plant is 100%, then the quantity of recycled paper pulped is calculated as 113% of the quantity of final paper produced. If the recycled paper content is less than 100%, the ratio of pulped recycled paper to produced paper is calculated as $recycled\ paper\ content[\%] * 1.13$, which assumes that the quantity of lost paper fibres in the pulping process is always 13%.

When estimating the quantity of pulped recycled paper from the paper production of a plant, the paper production rather than production capacity is used; meaning that if the collected data for the paper mill is production capacity, the calculated $p_y = p_{yc} * s_{util}$ is used. The result is correspondingly the actual production rather than production capacity. This is because recycled paper pulping and paper production are directly linked, but their capacities are not, due to different capacity utilization.

Once the annual production or production capacity for each plant is retrieved from online sources, or estimated, the annual energy demand e_y is calculated by Equation 1 in the case of production capacity, and Equation 2 in the case of production.

Allocation of NUTS-0 Production Method

Figure 10 presents an overview of the allocation of NUTS-0 data method. The NUTS-0 annual production data is obtained from national industrial associations when available, and otherwise from Table 42131-0003 from the Statistisches Bundesamt Genesis Online Database (Statistisches Bundesamt, 2019a). The NUTS-3 employment data is obtained from Table 42111-02-03-4-B from the Statistische Ämter Regional Databank (Statistische Ämter, 2019). The NUTS-0 employment data is obtained by summing the number of employees in a particular WZ08 branch across all NUTS-3 units in Germany.

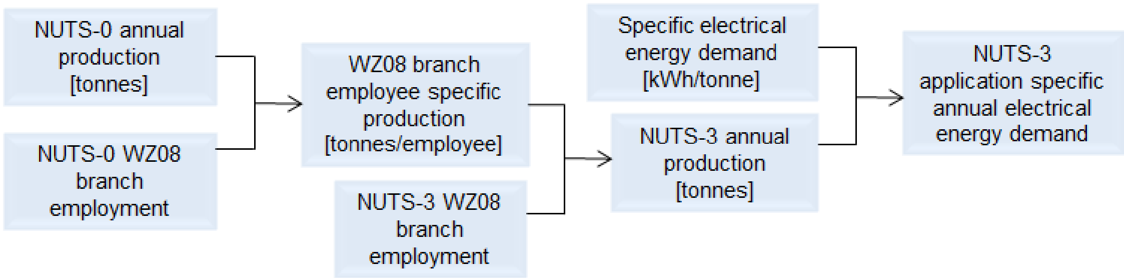

Figure 10: Allocation of NUTS-0 production method

This proposed method is comparable to that of Beer (2012) (refer to Figure 8), with the distinction that production data is disaggregated rather than electricity consumption, and the data being disaggregated is of a more detailed classification (product specific instead of WZ08 branch).

2017 NUTS-0 production data for cement is obtained from VDZ (2018), and 2018 NUTS-0 production data for mechanical wood pulp, recycled pulp, and paper is obtained from VDP (2019c). Both VDZ (2018) and VDP (2019c) are freely accessible online reports which are issued annually. Production data from industrial associations is preferred over the production data from Statistisches Bundesamt for two reasons, the first being it is more straightforward than extracting the production data from the government production data. The data from industrial associations avoids dealing with multiple product codes and multiple production data type columns in the Statistisches Bundesamt data table. The second reason is that for many products in the production data from Statistisches Bundesamt, only the quantity of product for sales, rather than the total quantity produced, is reported. As the quantity of product for sales may be less than the total quantity produced, this can result in lower than actual production. In addition, no Statistisches Bundesamt data for recycled paper pulping could be found.

Production data from an industrial association could not be found for air separation operations. Therefore, the production data from Statistisches Bundesamt Table 42131-0003 must be used. Table 8 shows the three air separation gases and their corresponding WZ08 nine digit subclass code for use with the Statistisches Bundesamt production data.

Table 8: Air separation NUTS-0 WZ08 nine digit subclass classification

Product	WZ08 Nine Digit Subclass Code
Argon	GP09-201111200
Nitrogen	GP09-201111600
Oxygen	GP09-201111700

When extracting the data from Statistisches Bundesamt Table 42131-0003, the total production is taken in preference to that production for sales when available.

In comparison to the production data, the industrial employment data is available at a significantly lower level of detail, at WZ08 branch classification level. WZ08 branches are relatively broad industry classifications, and include a variety of industrial products. The industrial processes load shifting applications, on the other hand, are a subcomponent of the WZ08 branches, and while they themselves are comprised of a number of individual products -ex. different types of paper produced by paper machines, and different gases produced by air separation- the applications are much more specific than the WZ08 branches that they are apart of. Table 9 specifies which WZ08 branch each load shifting application belongs to, and provides a short description of the WZ08 branches.

Table 9: Load shifting application versus WZ08 branch

Application	WZ08 branch
Cement Mills	WZ08-23: Production of glass and glassware, ceramics, and processing of stones and earth
Mechanical Wood Pulp	WZ08-17: Manufacture of paper, cardboard, and articles thereof
Recycled Pulp	WZ08-17: Manufacture of paper, cardboard, and articles thereof
Paper Machines	WZ08-17: Manufacture of paper, cardboard, and articles thereof
Air Separation	WZ08-20: Production of chemical products

The broadness of the WZ08 branch classification may limit the accuracy of the allocation of the NUTS-0 production data to the NUTS-3 level. More detailed employment data would be preferable, however the level of detail of industrial data at the NUTS-3 level provided by by statistical databanks is limited by the requirement for statistical confidentiality. According to Eurostat (2019b), data confidentiality is breeched if the data of a statistical unit (in the cases of industry, an industrial plant) can be identified either directly or indirectly, for example if there are only one or two plants of a certain type within the region. This is problematic at the NUTS-3 level because there are typically only one or two industrial plants of a given type at maximum within each individual NUTS-3 region; therefore detailed NUTS-3 industrial employment data is not publishable.

Allocation of NUTS-0 Energy Demand Method

Figure 11 presents an overview of the allocation of NUTS-0 energy demand method. The NUTS-0 electricity self generation data is obtained from Statistisches Bundesamt (2017b), the NUTS-0 electrical energy consumption data from Statistisches Bundesamt (2017a), and the NUTS-3 employment data from Table 42111-02-03-4-B from Statistische Ämter (2019). The NUTS-0 employment data is obtained by summing the number of employees in a particular WZ08 branch across all NUTS-3 units in Germany. Both the energy demand data and the employment data is categorized by WZ08 branch, as detailed in Table 9.

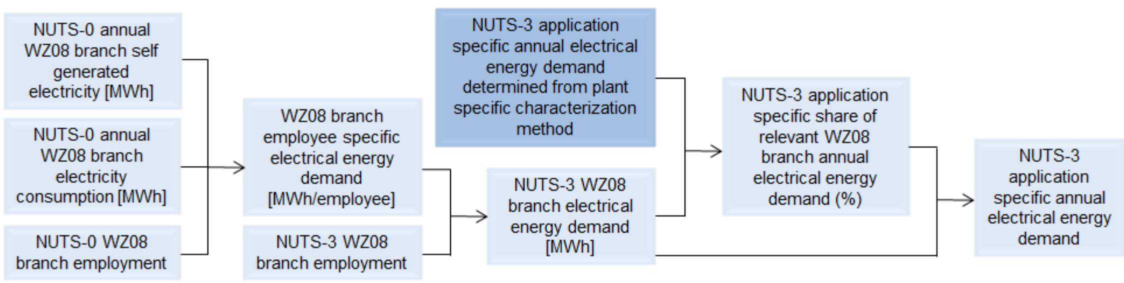

Figure 11: Allocation of NUTS-0 energy demand method

To calculate the total electrical energy demand per WZ08 branch, the quantity of self generated electricity and the quantity of electricity consumed from the grid are summed; this methodology was adapted from Beer (2012). The proposed allocation of NUTS-0 energy demand method is similar to that of Beer (2012) (refer to Figure 8), except for that it aims to generate application specific results instead of WZ08 branch results, which are rather broad.

To estimate the application specific annual energy demand, the method relies upon a characteristic application specific share of the corresponding WZ08 branch electrical energy demand per NUTS-3 region. An example would be cement milling being a predictable 10% of the total WZ08-23 branch electrical energy demand in each NUTS-3 region. If this characteristic share is known, then it can simply be applied to the NUTS-3 disaggregated electrical energy demand. The application specific shares must first be determined, however. This work aims to first determine if characteristic application specific shares of WZ08 branch annual electrical demand can be identified. In order to do so, the NUTS-3 WZ08 branch energy demand is compared against the previously calculated NUTS-3 application specific energy demand from the plant specific characterization method to determine the individual application's share of the WZ08 branch energy demand. The introduction of results from the plant specific characterization method is highlighted in Figure 11. The application share of the WZ08 branch electricity demand is calculated for each NUTS-3 region and analysed with the purpose of identifying a single representative share for each application.

For this method to be successful, the calculated application share of the corresponding WZ08 branch energy demand must be relatively similar across the different NUTS-3 regions. If characteristic application specific shares of WZ08 electrical energy demand can be identified, then these shares can be applied to the data obtained from Statistisches Bundesamt in the future, without re-preforming the plant specific characterization assessment.

NUTS-3 Total Industrial Energy Demand Method

This method aims to estimate the combined annual electrical energy demand of all load shifting applications, instead of application specific annual energy demand. Figure 12 presents an overview of the NUTS-3 total industrial energy demand method. NUTS-3 total industrial electrical energy consumed from the grid is provided directly in Table 4351-01-02-4 from Statistische Ämter (2019), however the self generated electricity is not available on a NUTS-3 basis. Thus, the NUTS-3 total industrial self generated electricity is estimated by allocating NUTS-1 total industrial self generated electricity data obtained from Statistisches Bundesamt (2017b) to NUTS-3 according to total industrial employment. The NUTS-3 industrial employment data is obtained from Statistische Ämter (2019) Table 42111-02-03-4-B, and the NUTS-1 industrial employment is calculated by summing the total number of industrial employees across all of the NUTS-3 regions belonging to each individual NUTS-1 region.

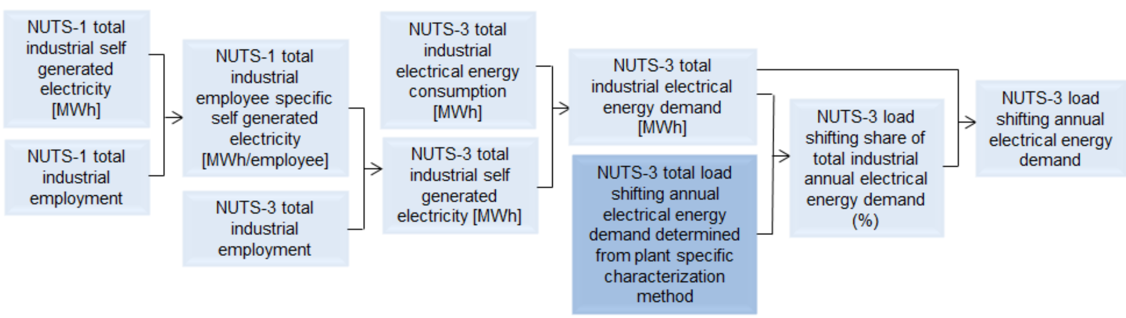

Figure 12: NUTS-3 total industrial energy demand method

Similar to the allocation of NUTS-0 energy demand method, the NUTS-3 total industrial energy demand method relies on the identification of a characteristic share; in this case the aggregated load shifting application annual energy demand share of the total industrial annual electrical energy demand on a NUTS-3 basis. For the NUTS-3 total industrial energy demand method to be successful, it must first be determined if such a characteristic share can be identified. To identify this share, the aggregated annual energy demand of the load shifting applications previously estimated using the plant specific characterization method is compared against the total industrial annual energy demand estimated from the statistical data, per NUTS-3 region. The introduction of results from the plant specific characterization method is highlighted in Figure 12. The purpose of this evaluation is that if a characteristic share across the NUTS-3 regions can be identified, then this share can be applied directly to the statistical data in the future without the need to re-preform the plant specific characterization method.

By aggregating the load shifting applications, NUTS-3 electrical energy demand data can be used directly, and in addition may provide a certain smoothing effect on the calculated shares of annual energy demand, resulting in overall more accurate estimations of NUTS-3 load shifting annual energy demand. The disadvantage is that the potential of the different industrial process applications will no longer be able to be differentiated.

3.2.5 Maximum Capacity

The NUTS-3 maximum capacity is calculated per application from the previously calculated annual energy demand according to Equation 8.

$$\Lambda = \frac{e_y}{8760 * s_{util}} \tag{8}$$

Where:
Λ = maximum capacity [MW]
e_y = annual energy demand [MWh]
s_{util} = capacity utilization [%]

This equation is an adaptation from Gils (2015) and Müller and Möst (2018) (refer to Equations 3 and 4), where the annual revision period is excluded from Gils (2015). In the formulation of Equation 3, Gils (2015) assumes that production capacity is the quantity of good which can be produced if the plant is operating at full load all year with the exception of a period of annual shutdown for revision (5% for all industries). However, this is simply an assumption on the part of Gils (2015).

In the course of gathering production capacity data, evidence was found indicating that production capacity is typically considered to be the quantity of good which can be produced if the plant is operating at full load for 365 days a year, with no annual revision considered. Thus, in this work it is assumed that production capacity corresponds to full load 100% of the year, and therefore f_{rev} is excluded.

3.3 Industrial Process Heat Load Shifting

To estimate the NUTS-3 PH annual energy demand, the methodology of Gils (2015) is adapted (refer to Gils (2015) Section 3.2.2). Gils (2015) methodology for estimating full load hours (refer to Gils (2015) Section 3.2.4), and selection of load profiles (refer to Gils (2015) Section 3.3.2) is also adapted. Full load hours are used in place of $8760 * s_{util}$ in Equation 8 to calculate maximum capacity. In this section, an overview of the adapted methodology will be provided, including the modifications made for use in this work.

Gils (2015) estimates NUTS-0 industry branch specific PH annual energy demand using 2009 branch total final annual energy demand data from Eurostat, and then disaggregates the NUTS-0 annual energy demands to NUTS-3 regions using employment data (refer to Gils (2015) Section 3.2.6). In this work, 2016 energy demand and employment is used. Industry is categorized according to the branches used by Eurostat in the presentation of the final energy demand data, refer to Table 10. In comparison to Gils (2015), the construction branch is excluded for three reasons: one being this work investigates the load shifting potential of producing industry, which does not include construction under the German WZ08 classification system. The second reason is that as construction is a mobile industry, establishing a viable system for thermal energy storage does not seem feasible. Additionally, Eurostat reports zero energy demand for the construction branch in Germany. The industrial final energy demand data from Eurostat is used rather than data from Statistisches Bundesamt because the data provided by Statistisches Bundesamt includes non-energy fuel consumption, whereas the data from Eurostat does not.

Table 10: Eurostat industry branches, corresponding data (Gils, 2015), and equivalent WZ08 branches (Eurostat, 2019a)

		Thermal annual full load hours			
	PH share [%]	<50 empl.	50-250 empl.	>250 empl.	Equivalent WZ08 branches
Metal	80.3	7400	7500	7600	24
Chemical and petrochemical	67.5	5000	7000	7000	20, 21
Minerals	81.4	4000	5500	7000	23
Mining and quarrying	60.0	4000	4000	4000	7, 8
Food, beverages, and tobacco	61.0	3000	3500	4500	10, 11, 12
Textile and leather	34.7	3500	4000	4000	13, 14, 15
Paper, pulp, and printing	65.1	3500	4000	5500	17, 18
Transport equipment	24.3	4000	5500	7000	29, 30
Machinery	26.3	5000	6000	7000	25, 26, 27, 28
Wood and wood products	34.7	4500	5000	5500	16
Other	41.7	4000	4000	4000	22, 31, 32

The Eurostat data is provided in seven tables based on the energy carrier category: electricity, gas, heat, oil, renewable energies (all biomass or renewable wastes for industry branches), solid fuels (mainly coal products), and wastes (Eurostat, 2016a,b,c,d,e,f,g). Most of the energy carrier categories are comprised of a number of sub-categories, but for the purposes of this work, the aggregated final energy demand for each category is taken or calculated for each industry branch. The total final annual energy demand for each branch can then be summed from the seven energy carrier categories.

From the total final annual energy demand data, PH final energy demand is estimated using branch specific shares of PH demand for Germany, based on Schlomann et al. (2010) (Gils, 2015). Refer to Table 10 for the PH shares, taken from Gils (2015). Gils (2015) goes on to further divide the PH final energy demand into subcategories based on temperature, and then excludes demands over 500 °C, but this is not done in this work as all forms of potential PH load shifting are under consideration, not exclusively CHP potential under the assumptions used by Gils (2015).

The NUTS-0 branch specific PH final energy demand is converted to useful energy demand using a representative conversion efficiency (Gils, 2015). The exchange of fuel based generation methods to electricity based generation methods results in a lower energy demand as a result of the higher efficiency of electricity based generation (Gils, 2015; Gruber et al., 2015). However, in doing so, thermal energy storage losses are not taken into account.

Gils (2015) uses national average conversion efficiencies based on energy carrier shares of the final energy demand from the Eurostat data. However, because branch specific breakdowns of the annual final energy demand per energy carrier are available, in this work branch specific average conversion efficiencies are used, as calculated from the 2016 Eurostat data. In calculating the average conversion efficiencies, the conversion efficiencies per fuel type used by Gils (2015) are used: 75% for coal and biomass, 80% for oil, 85% for gas, and 98% for electricity and heat.

The calculated NUTS-0 PH useful annual energy demands are then regionalized to the NUTS-3 level using NUTS-3 industrial branch employment data from Statistische Ämter (2019) Table 42111-02-03-4-B. The WZ08 branch data is aggregated according to the Eurostat branch categorization (refer to Table 10) to determine the NUTS-3 number of employees per Eurostat branch. It is advantageous to use employment data from Statistische Ämter (2019) instead of Eurostat employment data as used by Gils (2015), because Eurostat provides only total industrial employment rather than branch specific employment data on the NUTS-3 level. The NUTS-0 PH useful energy demand per branch is then disaggregated according to the branch specific share of total NUTS-0 employees per NUTS-3 region.

NUTS-0 branch employment data categorized by enterprise size class (Statistisches Bundesamt, 2016) is then used to estimate average full load hours for each branch, based on the enterprise size class dependent thermal full load hours obtained from Gils (2015) (refer to Table 10). NUTS-0 data must be used because NUTS-3 employment data divided by both industrial branch and enterprise size class is unavailable. The number of NUTS-0 employees per branch and size class is determined, again aggregating WZ08 branch data according to Eurostat branches, and then a weighted average of Gils (2015) full load hours is calculated using the relative share of total branch employees within each size class. The approach in this work is slightly different than in Gils (2015), as Gils (2015) approach is to determine the demand per enterprise in each country to evaluate the CHP potential per enterprise location.

Using the calculated full load hours, the appropriate PH load profile can be selected for each branch (refer to Gils (2015) Section 3.2.2 and Table D.2). The PH load profiles provided by Gils (2015) are one week in duration, which repeats throughout the year; seasonal variations are not taken into account. Figure 13 (from Gils (2015)) shows the weekly load profiles for the seven different full load hour categories. The same NUTS-0 average full load hours, and corresponding load profile for each branch is applied equally to each NUTS-3 region, therefore regional differences in the sizes of the companies within each branch are not taken into account. This is as a result of the lack of branch specific size class employment data on the NUTS-3 level.

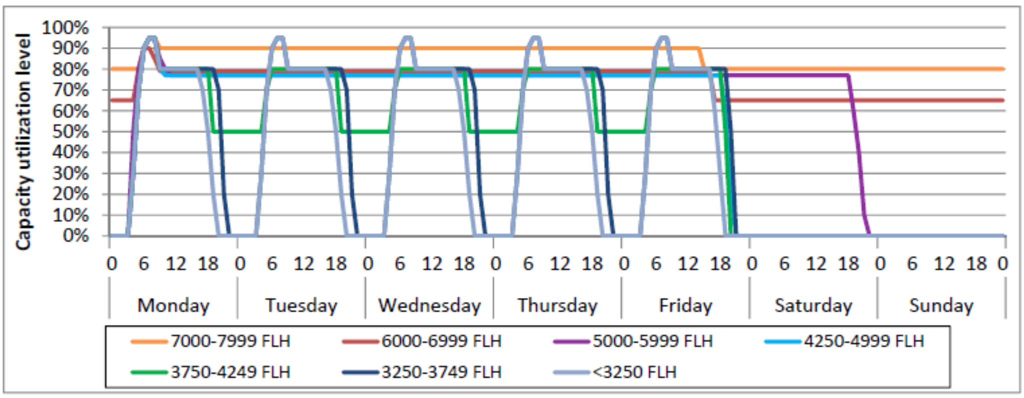

Figure 13: Process heat load profiles (Gils, 2015)

Having the NUTS-3 annual energy demand and maximum capacities, and load profiles, the only model inputs missing are Δt and f, which as previously discussed in Section 2.3, are not clearly defined for PH applications in the reviewed literature. Instead, different Δt and f will be tested within the time-resolved load shifting model to generate load shifting potentials in a similar range as estimated for the potential of industrial process applications. This will provide an idea of the relative scale of the potential of PH load shifting applications, as well as provide a preliminary view of the NUTS-3 distribution of PH load shifting potential within Germany.

Figure 14 provides an overview of the above described methodology used to determine the time-resolved model inputs for industrial process heat.

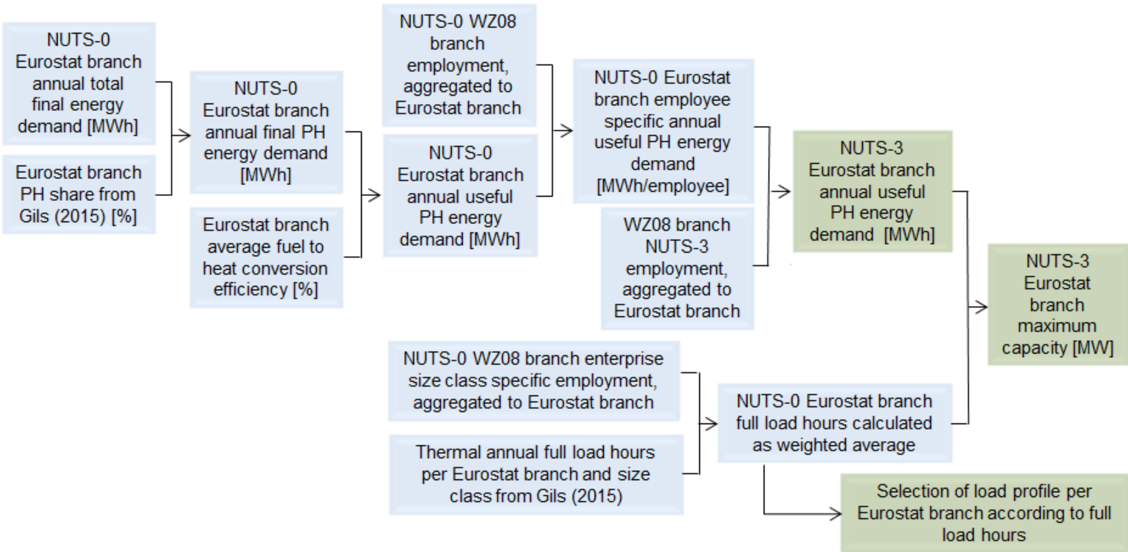

Figure 14: Process heat method

In regards to the time-resolved load shifting model, a modification is made to the power envelope equation for modelling of the PH load shifting potentials; instead of using f_{inc}, and f_{dec}, only a single f value will be used. This means that instead of establishing a constant, non-zero minimum load using $\Lambda * f_{dec}$, $P_{min}(t)$ is calculated as a percentage of $L(t)$, in the same way that $P_{max}(t)$ is calculated as a percentage of the difference between the maximum capacity and $L(t)$. With this modification, f in the case of PH load shifting potential is intended to directly indicate the share of flexilizable load. In applying f to entire aggregated PH load, the distinction between currently electrically or fossil fuel generated PH, or any individual applications within the two categories are not taken into account. It is simply assumed that a certain percentage of the total PH load is electrified and made flexible in the future.

The modified power envelope equations is presented in Equation 9. The energy envelope equation remains unmodified (Equation 6).

$$P_{max}(t) = (\Lambda - L(t))f \tag{9a}$$
$$P_{min}(t) = -L(t) * f \tag{9b}$$

3.4 Future Projections

The future projections for industrial process load shifting potentials are estimated using a methodology modelled after Gils (2015), in which the future potential is calculated based on future projections of annual energy demand. Any future changes in the load profile, Δt, f_{inc} and f_{dec}, and s_{util} are not taken into account.

From Equation 2, annual energy demand is calculated using annual production, and specific electrical energy demand, therefore future developments in both need to be projected in order to estimate future load shifting potential. In this work, past trends in production and energy demand are analysed in order to project future developments. Production and energy demand data is obtained from industrial associations publications, as well as Statistisches Bundesamt. NUTS-0 future load shifting potential is estimated rather than NUTS-3, because while national industrial trends can be analysed and forecasted, it is not possible to predict which individual industrial plants will close or change production, and at which locations new plants will open at in the future.

Following the estimation of future annual energy demands, Λ, $L(t)$, $P_{max}(t)$, $P_{min}(t)$, $E_{max}(t)$, and $E_{min}(t)$ are determined using the same methods described in Sections 3.2.5, 3.2.3, and 3.1. The same model inputs as in Table 7 are used, with the exception of specific electrical energy demand (e_i) which may change in the future due to industrial energy efficiency developments.

4 Results and Discussion

This section presents and analyzes the results of the study, including the estimated load shifting potential of industrial processes, industrial process heat, and the future estimation of load shifting potential for the industrial process applications. First, the results of the regionalization of the annual energy demand for the industrial processes are presented, with the purpose of determining whether any of the proposed alternative methods can adequately estimate NUTS-3 industrial annual energy demand in comparison with the significantly more work intensive plant specific characterization method. It is found that none of the three proposed alternative methods are able to adequately replicate the results of the plant specific characterization method. Therefore, when estimating the load shifting potential for industrial processes using the time-resolved load shifting model in Section 4.2.1, the NUTS-3 annual energy demand results from the plant specific characterization method are used.

4.1 Regionalization of Industrial Processes Annual Energy Demand

After gathering the required data, the four methods for regionalization of annual energy demand of industrial processes load shifting applications were executed using Python. The Python scripts and corresponding input and output data can be accessed from the linked online repository[5]. In this section, the results of the plant specific characterization method will first be evaluated, then in the following subsections the results of the three methods developed for use with easily accessible statistical data will be compared against the plant specific characterization method.

4.1.1 Plant Specific Characterization Method

In the course of conducting the plant specific characterization method, a dataset of German industrial plants belonging to the industrial process applications selected for analysis in this work was compiled. The dataset of industrial plants and their corresponding location and production

[5] `https://doi.org/10.5281/zenodo.3613767`

capacity or reported production is available from the online repository. This compiled dataset is useful because the previously published studies which evaluated site specific DR potential (Gils, 2015; Gruber et al., 2014) have not published the underlying plant specific data. The dataset contains the most recent plant data which could be obtained though online sources as of the time of conducting this work in 2019. However, it must be noted that some of the individual data sources that are used are several years old. The individual sources behind all of the data collected is provided along with the dataset. In total there are 45 identified cement mills - one of the locations listed by VDZ has only mixing, and no grinding operations -, 8 mechanical wood pulping operations, 68 recycled paper pulping operations, and 115 paper mills. No industrial association or otherwise consolidated list of air separation plants could be found, therefore plant specific characterization for air separation operations could not be accomplished.

As an initial check on the accuracy of the collected and estimated production data, the production of all of the plants for each application are summed to determine the total NUTS-0 production, in order to compare with NUTS-0 production data reported by the corresponding national industry association. For plants for which production capacity was recorded, s_{util} is used to estimate the production. Table 11 presents the results.

Table 11: Plant specific characterization method NUTS-0 production

Application	Resulting NUTS-0 Production [tonnes]	NUTS-0 Production [tonnes] from Industry Association	Percent Difference
Cement Mills	36.3 million	34.0 million (VDZ, 2018)	6.8 %
Mechanical Wood Pulp	0.84 million	0.81 million (VDP, 2019c)	3.6 %
Recycled Pulp	16.6 million	17.2 million (VDP, 2019c)	3.5 %
Paper Machines	22.4 million	22.7 million (VDP, 2019c)	1.3 %

Compared against the results of the reported NUTS-0 production from VDZ and VDP, the overall NUTS-0 production results of the plant specific characterization method are satisfactorily accurate. The largest deviation from reported NUTS-0 production is for cement mills, at 6.8% higher. Considering that the estimated production is calculated in part with s_{util}, this higher estimated production may indicate that the actual s_{util} of cement mills is lower than the 70% selected based on the reviewed literature. An s_{util} closer to that of Gruber et al. (2014) and Müller and Möst (2018) (63% and 60% respectively) may be more appropriate.

Figure 15 presents the NUTS-3 regionalized annual energy results of the plant specific characterization method. The cement milling and mechanical wood pulping regional distribution can be compared against the application specific NUTS-3 DR potential maps from Gruber et al. (2014). Both the cement milling and mechanical wood pulping NUTS-3 distributions agree well with the distributions shown by Gruber et al. (2014). The most notable difference is that the maps of Gruber et al. (2014) identifies a select number of NUTS-3 regions as having cement milling and mechanical wood pulping operations which Figure 15 does not: seven for cement milling, and two for mechanical wood pulping. In regards to cement plants, the observed difference between Gruber et al. (2014) and Figure 15 may be due to the presence of plants which are not members of VDZ, which are not taken into account in this work. In regards to mechanical wood pulping, the difference is likely due to closing of wood pulping operations since the writing of Gruber et al. (2014). From Mantau et al. (2018), nine mechanical wood pulping operations closed between 2005 and 2016.

Overall, the results presented in Table 11, and Figure 15 indicate that despite the estimations required for plants which lack publicly accessible production data (refer to Section 3.2.4), the plant specific characterization method is able to estimate production and NUTS-3 spatial distribution of industrial plants in Germany with relatively good accuracy.

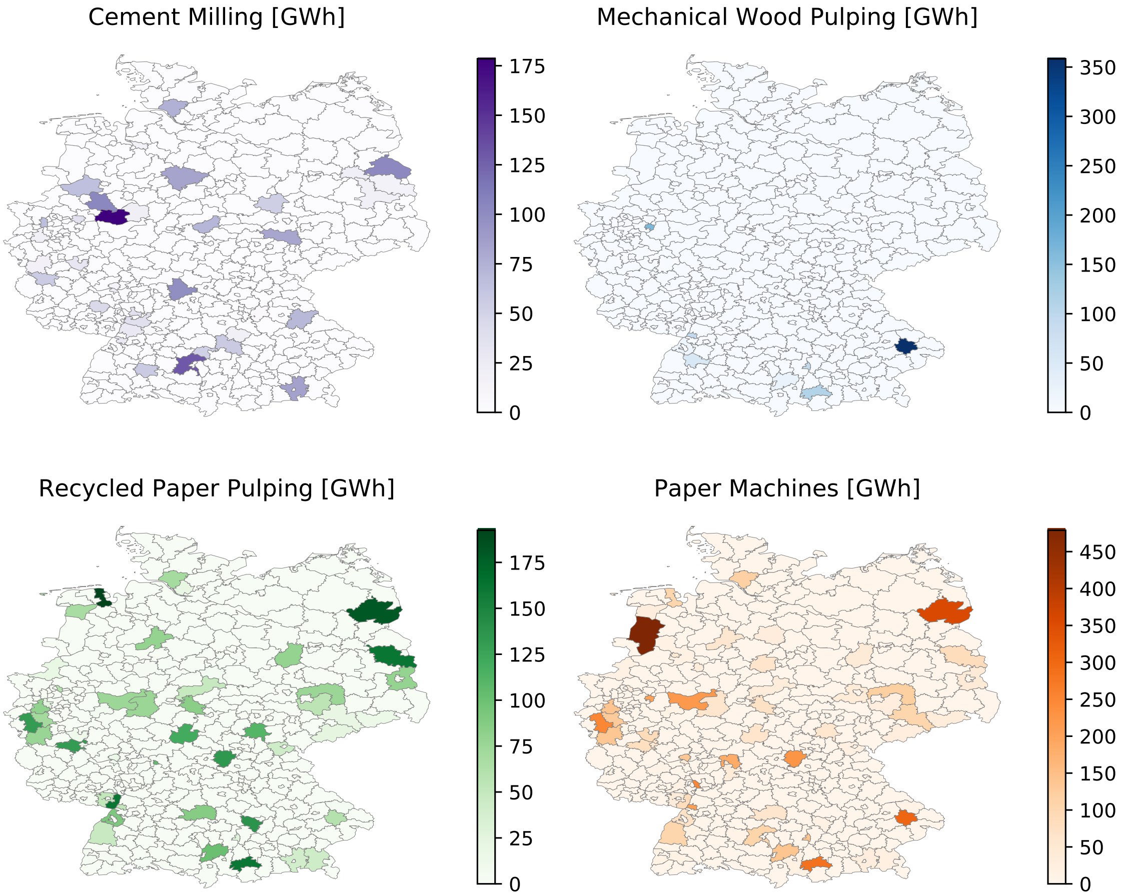

Figure 15: NUTS-3 annual energy demand results from plant specific characterization method

4.1.2 Allocation of NUTS-0 Production Data Method

Figure 16 compares the results of the allocation of NUTS-0 production data method with the results of the plant specific characterization method for the four load shifting applications which were able to be evaluated using the plant specific characterization method (excludes air separation). Each point on the scatter plots represents one NUTS-3 region, with the x and y coordinates being the annual energy demand from the plant specific characterization method, and from the allocation of NUTS-0 production data method, respectively. If the allocation of NUTS-0 production data method result for a given NUTS-3 region is equal to the plant specific characterization method, the point would lie along the $x = y$ line. The closer the points are to the $x = y$ line, the more accurately the allocation of NUTS-0 production data method replicates the plant specific characterization method.

The results presented in Figure 16 show overall that the allocation of NUTS-0 production data method does not accurately replicate the results of the plant specific characterization method. For all four load shifting applications, the points do not lie close enough to the $x = y$ line to instill any confidence in the allocation of NUTS-0 production data method. The closeness of fit to the $x = y$ line is quantified by the root mean square error (RMSE) displayed alongside the scatter plots in Figure 16. Both the total RMSE and the RMSE excluding all NUTS-3 regions for which both the annual energy demand from the plant specific characterization method and allocation of NUTS-0 production method is zero are shown. Instances of zero GWh from both methods are instances of correct estimation by the allocation of NUTS-0 production method, but are excluded to quantify how well the allocation of NUTS-0 production method assesses the annual energy demand of the remaining NUTS-3 regions. The RMSE in all cases are too high to qualify an adequate model fit.

The total NUTS-0 production values used in the allocation of NUTS-0 production data method are the production data from the industry associations VDZ and VDP, shown in Table 11, which agree well with the NUTS-0 production results of the plant specific characterization method. Therefore, the disagreement between the two methods must stem from the allocation of the NUTS-0 production data.

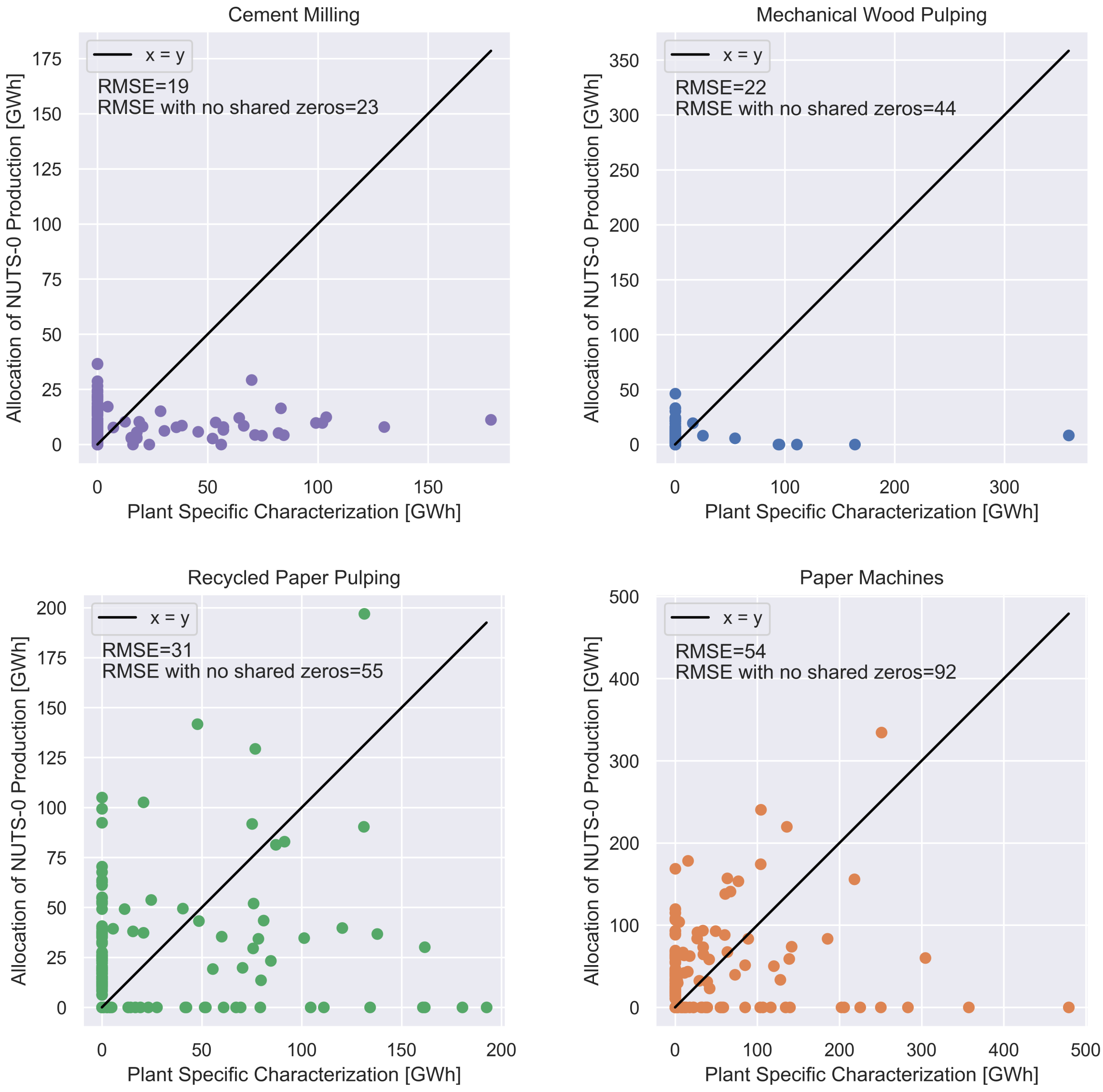

Figure 16: Comparison of NUTS-3 annual energy demand from allocation of NUTS-0 production data method and plant specific characterization method

The most apparent issue is the large numbers of points lying along the vertical and horizontal zero axes. Points lying along the vertical zero axis represent NUTS-3 regions for which according to the plant specific characterization method, the annual energy demand for the associated load shifting application is zero, but the result of the allocation of NUTS-0 production data method is non-zero. This problem can be attributed to misallocated production of the particular product due to the broad nature of the WZ08 branches. For example, in a given NUTS-3 region, there may be several glassware and ceramics plants, but zero cement plants. Because the number of employees in the cement and glassware or ceramics industries cannot be distinguished between in the employment data, production is misallocated to this NUTS-3 region with no cement plants. This is the case for a large number of NUTS-3 regions concerning all load shifting applications.

Even regarding recycled paper pulping and paper machines, for which the WZ08-17 branch 'manufacture of paper, cardboard, and articles thereof' appears by name to be adequately narrow to accurately allocate production according to employee data, Figure 16 shows that it is not. This branch also includes industrial plants which process raw paper and board into finished products such as notebooks and cardboard boxes, and it is apparent from Figure 16 that employment from plants such as these causes significant misallocation of paper production.

Misallocation of production to NUTS-3 regions without any plants results in less production being allocated to the NUTS-3 regions with plants. This problem is particularly noticeable in the cement milling subplot.

The second clear problem is the large number of NUTS-3 regions for which the annual energy demand according to the allocation of NUTS-0 production data method is zero, but from the plant specific characterization method is non-zero. This is most likely a result of unpublished employment data for these NUTS-3 regions as a result of there being an insufficient number of plants of the particular WZ08 branch to guarantee confidentiality. As can be seen from the points lying far along the horizontal zero axes in Figure 16, some of these singular plants have very high production, and correspondingly high annual energy demand which the allocation of NUTS-0 production data method is unable to identify.

4.1.3 Allocation of NUTS-0 Energy Demand Data Method

As explained in Section 3.2.4, the allocation of NUTS-0 energy demand data method relies on a characteristic application specific share of the corresponding WZ08 branch electrical energy demand per NUTS-3 region. Thus, the application shares of the WZ08 branch electrical energy demand first have to be analyzed to determine whether characteristic application specific shares across the NUTS-3 regions of Germany can be identified. Refer back to Section 3.2.4 and Table 9 for clarification on the difference between WZ08 branches and the load shifting applications. The NUTS-3 WZ08 branch annual energy demand is estimated according to the allocation of NUTS-0 energy demand data method (refer to Section 3.2.4), and the NUTS-3 application specific annual energy demand is obtained from the plant specific characterization method, the results of which are presented in Section 4.1.1.

When the application shares of the WZ08 branch annual energy demand were calculated, it was found that similar to the allocation of NUTS-0 production method, there are a disproportionately large number of cases for which the allocation of NUTS-0 energy demand data method either incorrectly identifies non-zero annual energy demand for NUTS-3 regions in which there is zero application specific annual energy demand, or vice versa for all four applications. This problem makes it inaccurate to apply any defined application share of NUTS-3 WZ08 branch annual energy demand because a significant quantity of energy demand would be allocated to NUTS-3 regions with no existing industrial load shifting applications, and many NUTS-3 with existing industrial load shifting applications would not be assigned any energy demand at all. Thus, a representative share of WZ08 branch annual energy demand cannot be selected, and the method will not be pursued further.

The problems encountered with the allocation of NUTS-0 annual energy demand data method mirrors the problems discussed regarding the allocation of NUTS-0 production data method. It is therefore concluded that NUTS-3 WZ08 branch employment data is an inadequate basis for regionalization of application specific information. Inferring from the presented results, it appears to have the problem of being both too broad to accurately represent the individual industrial load shifting applications attempting to be modelled, and at the same time being too narrow in a considerable number of NUTS-3 regions, for which WZ08 branch employment cannot be reported due to the requirement for statistical confidentiality.

4.1.4 NUTS-3 Total Industrial Energy Demand Method

Similar to the allocation of NUTS-0 annual energy demand method, in order to utilize the NUTS-3 total industrial energy demand method, a characteristic share must first be identified. In the case of the NUTS-3 total industrial energy demand method, it must be determined whether the aggregated NUTS-3 annual energy demand of the four load shifting applications evaluated by the plant specific characterization method constitutes a defined percentage of the total industrial annual energy demand across the different NUTS-3 regions.

From the calculated shares however, it is found that despite aggregating the annual energy demand of all industrial process load shifting applications and using NUTS-3 energy demand data directly rather than disaggrating according using employment data, the annual energy demand of the load shifting applications do not constitute a characteristic share of the total industrial energy demand. Similar to the results of the allocation of NUTS-0 production, and allocation of NUTS-0 annual energy demand methods, there are a large number of NUTS-3 regions for which the annual energy demand determined by the NUTS-3 total industrial energy demand method is non-zero, but the load shifting energy demand from the plant specific characterization method is zero. Therefore, a representative share of total industrial annual energy cannot be selected, and this method will not be pursued further.

4.2 Load Shifting Potential

In this section, the load shifting potential results from the time-resolved load shifting model are presented and discussed; first the load shifting potential for the industrial processes, and then in following the load shifting potential for industrial heat demand. The time-resolved load shifting model was implemented using Python; the input data, script, and complete results from which can be accessed from the online repository.

4.2.1 Industrial Processes

From the results presented in Section 4.1, it is concluded that the allocation of NUTS-0 production data method, allocation of NUTS-0 energy demand data method, and the NUTS-3 total industrial energy demand method are not able to estimate NUTS-3 energy demand for industrial processes with sufficient accuracy. Thus, the NUTS-3 annual energy demand from the plant specific characterization method is selected for further use with the load shifting model. However, as mentioned in Section 4.1.1, it was not possible to evaluate air separation plants using the plant specific characterization method. As a second best alternative, the annual energy results of the allocation of NUTS-0 production data method are used to estimate the load shifting potential for air separation plants, although the accuracy of the NUTS-3 distributions is limited.

The NUTS-3 annual energy demand is used along with the load profiles described in Section 3.2.3 to generate the scheduled load curves $L(t)$, which subsequently act as input to the time-resolved load shifting model. Each of the 401 NUTS-3 regions have a unique $L(t)$ for each of the five applications, resulting in 2005 $L(t)$ annual time series. There are also 2005 corresponding NUTS-3 maximum capacities (Λ) which are calculated according to Equation 8.

The scheduled load time series, along with the three other key model inputs Δt, Λ, and $f_{inc}\&f_{dec}$ are used to determine the power and energy envelopes for each NUTS-3 region and application according to the methdology described in Section 3.1. The power and energy envelopes are comprised of $P_{max}(t)$, $P_{min}(t)$, $E_{max}(t)$, and $E_{min}(t)$, and together characterize the load shifting potential of the particular application. For the applications with a constant load profile, the power and energy envelopes are also constant; however, if an application has a varying load profile, the power and energy envelopes also vary with time. In the case of the industrial processes analysed in this work, only the load shifting potential of cement mills is time dependent.

The complete numerical results from the time-resolved load shifting model can be accessed from the online repository, and consist of a total of 8020 annual time series - four envelope boundaries for each application and each NUTS-3 region. For purposes of analysis in this work, NUTS-3 maps of $P_{max}(t)$, $P_{min}(t)$, $E_{max}(t)$, and $E_{min}(t)$ annual average values, and NUTS-0 annual time series for $L(t)$, $P_{max}(t)$, $P_{min}(t)$, $E_{max}(t)$, and $E_{min}(t)$ will be presented for each application.

Positive Balancing Power (P_{max})

Figure 17 shows the NUTS-3 annual average $P_{max}(t)$ maps for each application, and the total average $P_{max}(t)$ for all five applications combined. With the perspective of load shifting applications as an equivalent energy storage device, $P_{max}(t)$ is the maximum charging power. In other terms, $P_{max}(t)$ is the maximum extent by which the load shifting application can increase its load.

The NUTS-3 distribution of $P_{max}(t)$ mirrors the NUTS-3 distribution of annual energy in Figure 15, as does the average $P_{min}(t)$ distribution in Figure 18 and energy storage capacity in Figure 19. This is as expected because calculation of $L(t)$ and in turn, the power and energy envelopes are proportional to the annual energy demand (e_y). The main distinctions between the maps are the scale and units.

For each application, there are one or two NUTS-3 regions which stand out as having particularly high load shifting potential, and there are many NUTS-3 regions which do not have any industrial processes load shifting potential; but overall, the NUTS-3 regions which do have some level of industrial processes load shifting potential are relatively evenly distributed geographically across Germany. In other terms, there is no particularly obvious concentrated region for industrial processes load shifting potential, such as the Ruhr region, which is a well-known industrial area in Germany. However, there is a noticeable region in the north-east area of Germany which has a low degree of load shifting industry, comprised of Mecklenburg-Vorpommern and neighbouring parts of Brandenburg, Sachsen-Anhalt, Niedersachsen, and Schlewsig-Holstein.

There are several important location factors for the different industrial applications. Important location factors for cement mills are: a nearby limestone quarry, close proximity to sales markets, and competitive electricity prices (VDZ, 2013a,b). Important factors for paper mills are access to water, energy, and the necessary raw materials (APV Darmstadt and VPM, 2014).

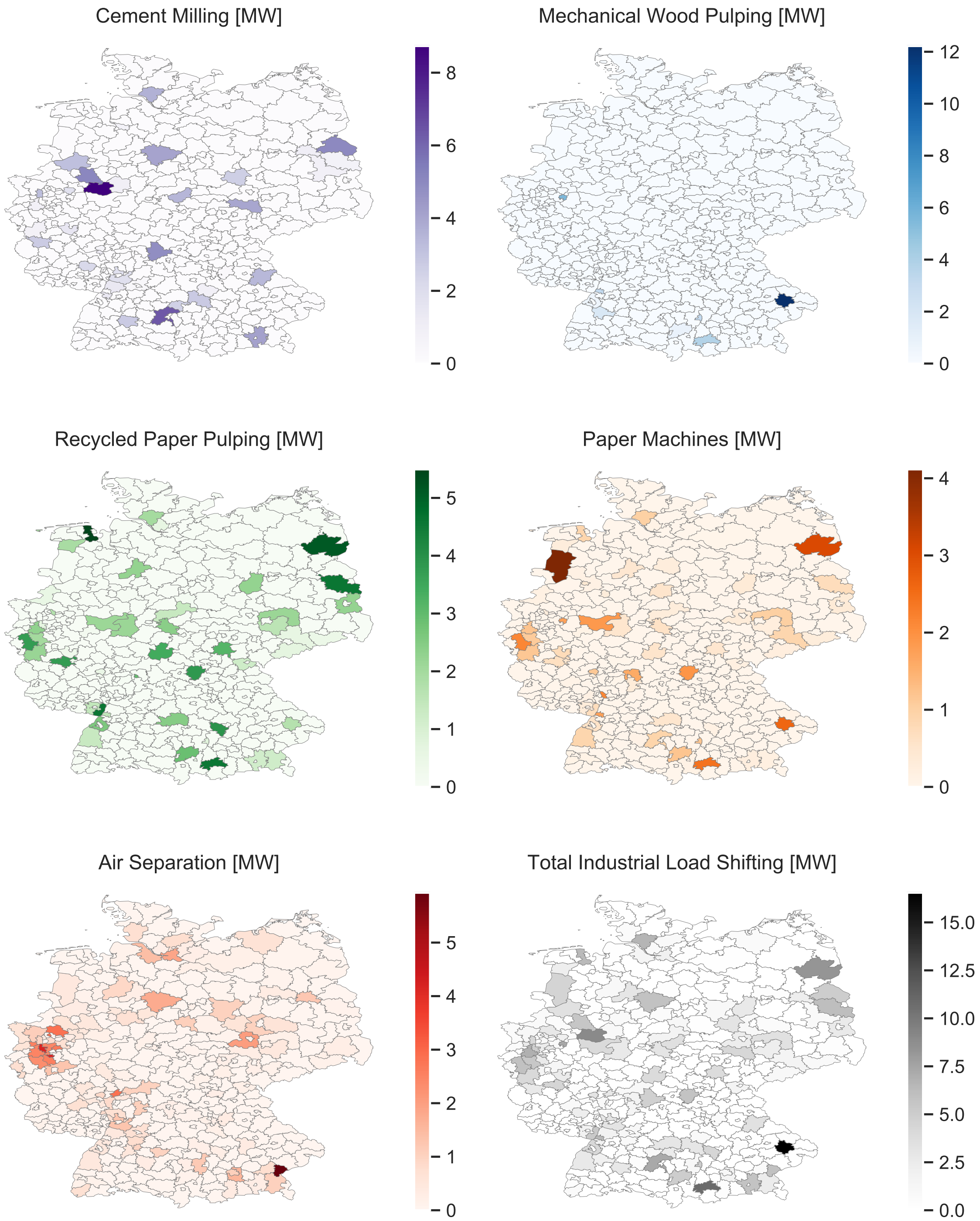

Figure 17: NUTS-3 annual average maximum charging power ($P_{max}(t)$)

It is difficult to compare the NUTS-3 load shifting potential results from this work to results in previously published literature because so few NUTS-3 industrial load shifting studies have been published; only Gruber et al. (2014), and FfE (2016) (which takes their results for industrial processes from Gruber et al. (2014)) were identified. In addition, the results of Gruber et al. (2014) are only available graphically with five graduated categories of load shifting potential; the full numerical results are not accessible. Gruber et al. (2014) also analyses only negative balancing power potential ($P_{min}(t)$), and shares only two applications in common with the current work: cement milling and mechanical wood pulping. Thus, the extent to which a NUTS-3 comparison is possible is limited. Instead, the NUTS-0 results of this work will be compared with the results across literature to enable a more extensive comparison.

It must be noted that the estimations of the load shifting potential for industrial processes are highly dependent on the decisions made by the individual researchers, such as regarding specific energy demand (e_i), utilization (s_{util}), and the flexible component (f), and therefore vary widely across literature. In addition, differing methodologies, the year of the study and corresponding data, and different sources for production data or installed capacity have a significant impact on the results.

Table 12 compares the NUTS-0 average positive balancing power for Germany from the current work with the results from other works across literature. And as $P_{max}(t)$ is closely related to maximum capacity, the maximum capacity from the current work as well as the other reviewed works is presented alongside the P_{max} results, in Table 13. The total NUTS-0 annual average estimated $P_{max}(t)$ potential in this work is 376 MW.

Table 12: NUTS-0 $P_{max}(t)$ [MW] comparison across literature

	Cement Mills	Mechanical Wood Pulp	Recycled Pulp	Paper Machines	Air Separation
Klobasa (2007)	-	-	-	-	-
Paulus and Borggrefe (2011)	0	62	-	-	-
VDE (2012)	313	0	-	0	-
Gruber et al. (2014)	-	-	-	-	-
Gils (2015)	105	62	112	125	61
Müller and Möst (2018)	-	-	-	-	-
Current work	91	31	104	53	97

Table 13: NUTS-0 Λ [MW] comparison across literature

	Cement Mills	Mechanical Wood Pulp	Recycled Pulp	Paper Machines	Air Separation
Klobasa (2007)	-	-	-	-	-
Paulus and Borggrefe (2011)	314	312	-	-	-
VDE (2012)	313	268	-	2000	-
Gruber et al. (2014)	-	-	-	-	-
Gils (2015)	-	-	-	-	-
Müller and Möst (2018)	-	-	-	-	-
Current work	302	136	762	521	485

In regards to cement, it is important to consider that the figures given by Gils (2015) and the current work are averages of the annual $P_{max}(t)$ time series, whereas VDE (2012) provides the maximum $P_{max}(t)$ value assuming all cement mills in Germany are ramped-up from zero load to maximum capacity. Comparing the estimated maximum capacity rather than P_{max}, the result of the current work of 302 MW compares well with that estimated by other studies (3.5% difference). Paulus and Borggrefe (2011) estimate a NUTS-0 cement mill capacity of 314 MW and s_{util} of 80%, but from their findings through communication with industry, assumes that cement mills cannot increase their load. The average $P_{max}(t)$ for cement mills compares fairly well between the current work and Gils (2015) (14% difference), despite significantly different choices for e_i, s_{util}, and load profile.

The P_{max} for mechanical wood pulp at 31 MW is approximately 50% lower than that estimated by Paulus and Borggrefe (2011) and Gils (2015). This difference is likely due to a combination of closing of mechanical wood pulp operations over the recent past (Mantau et al., 2018), and a higher e_i selected by Gils (2015). As previously mentioned in Section 4.1.1, from Mantau et al. (2018), nine mechanical wood pulping operations closed between 2005 and 2016, approximately half of the 17 locations originally in operation. VDE (2012) reports a maximum capacity of 268 MW and s_{util} of 78% for mechanical wood pulp, but does not report a positive balancing power potential. The maximum capacity for mechanical wood pulping from the current work is also approximately 50% lower than that estimated by past works.

The estimated P_{max} for recycled paper pulping from the current work compares reasonably well with Gils (2015), but is significantly (58%) lower in regards to paper machines. The reason for this discrepancy is unknown, particularly considering the similar s_{util}, identical f_{inc}, and that the total NUTS-0 annual energy demand for paper machines determined in this work of 6206 GWh is greater than the 4921 GWh reported by Gils (2015).

In regards to air separation, the estimated P_{max} from Gils (2015) of 61 MW is 37% lower than that estimated by the current work. As s_{util}, and f_{inc} were adopted directly from Gils (2015), the difference must be attributed to a higher annual energy demand. The estimated NUTS-0 total energy demand for air separation from the current work is 3400 GWh, compared to 2674 GWh reported by Gils (2015). Because e_i for air separation was also adopted from Gils (2015), the root origin of the discrepancy must be differing production values. The source of the production data in Gils (2015) is unknown.

Negative Balancing Power (P_{min})

Figure 18 shows the NUTS-3 annual average $P_{min}(t)$ maps for each application, and the total average $P_{min}(t)$ for all five applications combined. $P_{min}(t)$ is the maximum extent by which a load shifting application can decrease its load. From the perspective of load shifting applications as an equivalent energy storage device, $P_{min}(t)$ is the maximum available discharging power.

The NUTS-3 maps for cement milling and mechanical wood pulping in Figure 18 can be compared with Figure 3 and 4 in Gruber et al. (2014). For cement milling, it must be considered that Gruber et al. (2014) considers raw mills to be suitable for load shifting, whereas they are excluded in the current work. In addition, Gruber et al. (2014) does not consider a winter shut-down period for cement, as there is in the current work. Therefore, the average cement milling potential estimated here would be expected to be lower than that estimated by Gruber et al. (2014).

The highest P_{min} for an individual NUTS-3 region as shown in Figure 4 in Gruber et al. (2014) is 21 MW, whereas the highest P_{min} for an individual NUTS-3 region in the current work is approximately 70% lower at 6 MW.

In regards to mechanical wood pulping, from Figure 3 in Gruber et al. (2014), the highest reported P_{min} for an individual NUTS-3 region is 67 MW. The highest P_{min} shown in Figure 18 of the current work is approximately 40 MW, which is 40% lower. This is most likely attributed to the lower e_i selected for mechanical wood pulp, which is approximately 50% lower than that used by Gruber et al. (2014) (refer to Table 5). As discussed in Section 3.2.4, the mechanical wood pulping specific energy values found in the reviewed literature are outdated; the mechanical wood pulping e_i used by Klobasa (2007) and Gruber et al. (2014) originates from a 2003 source. The more recent source adopted in the current work is assumed to be more accurate, thus the difference between the current work and Gruber et al. (2014) is acceptable.

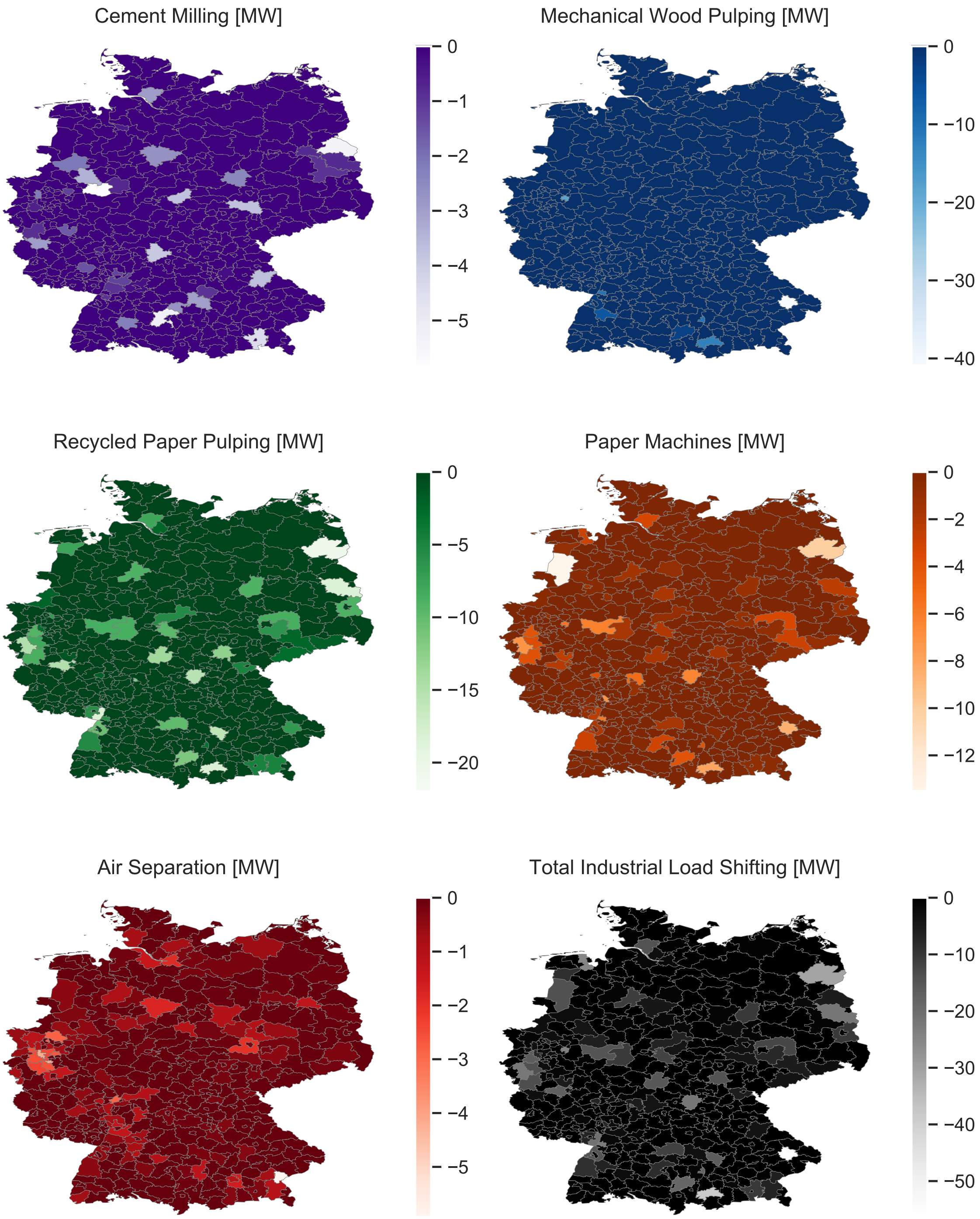

Figure 18: NUTS-3 annual average maximum discharging power ($P_{min}(t)$)

Table 14 compares the NUTS-0 average negative balancing power for Germany from the current work with the results from other works across literature. The wide ranges in the results from previous studies in Table 14 illustrate the significant differences observed between different studies over the past decade. For example, the 270 MW range in the reported P_{min} for cement mills, 190 MW range for mechanical wood pulping, and 1500 MW range for paper machines. The total NUTS-0 annual average estimated $P_{min}(t)$ potential in this work is -871 MW.

Table 14: NUTS-0 $P_{min}(t)$ [MW] comparison across literature

	Cement Mills	Mechanical Wood Pulp	Recycled Pulp	Paper Machines	Air Separation
Klobasa (2007)	180	400	-	-	170
Paulus and Borggrefe (2011)	251	250	-	-	-
VDE (2012)	313	208	-	1700	-
Gruber et al. (2014)	150	310	-	-	-
Gils (2015)	422	249	449	204	51
Müller and Möst (2018)	-	-	-	-	-
Current work	77	105	417	175	97

The average NUTS-0 $P_{min}(t)$ of 77 MW for cement mills from the current work is significantly lower (at least 50%) than the results of the reviewed studies. However, there are several relevant reasons for this. One reason is that Klobasa (2007), Gruber et al. (2014), and Gils (2015) assume a greater number of cement process steps as being suitable for load shifting, such as raw milling. For example, from Table 5, Gils (2015) uses a specific energy for cement production which is more than twice of that selected for use in the current work, and which is representative of the entire cement production chain. Klobasa (2007) and Gruber et al. (2014) use specific energies which are in total higher than that reported in Table 5, the values in Table 5 are only their reported values for the cement milling process step. A higher e_i results in a higher $L(t)$, which results in a higher estimated decreasable load (P_{min}).

In addition, Paulus and Borggrefe (2011) and VDE (2012) do not consider any limitation on the flexibility of cement mills, as Klobasa (2007), Gruber et al. (2014), and Gils (2015) do. The P_{min} reported by the current work and Gils (2015) are also annual averages considering a decrease in load during the winter, whereas the other sources either assume a constant load, or are reporting the maximum $P_{min}(t)$, such as VDE (2012).

Despite taking into account a decrease in load during the winter, as well as a limitation on the flexibility of cement mills, the P_{min} for cement mills of 422 MW from Gils (2015) is notably higher than the other studies reviewed. In comparison to the next most recent study, Gruber et al. (2014), the 50 % lower P_{min} estimated by the current study is perhaps reasonable considering the exclusion of raw mills and incorporation of a decrease in load during the winter.

The estimated P_{min} of 105 MW for mechanical wood pulping is also approximately 50% lower than the lowest reported value from the reviewed literature. As with the lower estimated P_{max} for mechanical wood pulping, this may be attributed to closing down of mechanical wood pulping operations, and a lower e_i selected in the current work.

The P_{min} for recycled paper pulping and paper machines reported by Gils (2015) compares relatively well (14 % difference) with that estimated by the current study. The P_{min} reported by VDE (2012) is disregarded as being unreasonably high.

In regards to air separation plants, as with P_{max}, the P_{min} estimated by the current study is significantly higher than Gils (2015), but is also significantly lower than that reported by Klobasa (2007). This again demonstrates the large range possible amongst different studies.

Energy Storage Capacity (E_{max} and E_{min})

Figure 19 depicts the NUTS-3 annual average storage capacity results for the five different industrial process load shifting applications, as well as the aggregated total storage capacity. The average $E_{max}(t)$ and $E_{min}(t)$ are in fact equivalent to each other, but with opposite signs, thus only one NUTS-3 map will be shown to avoid redundancy.

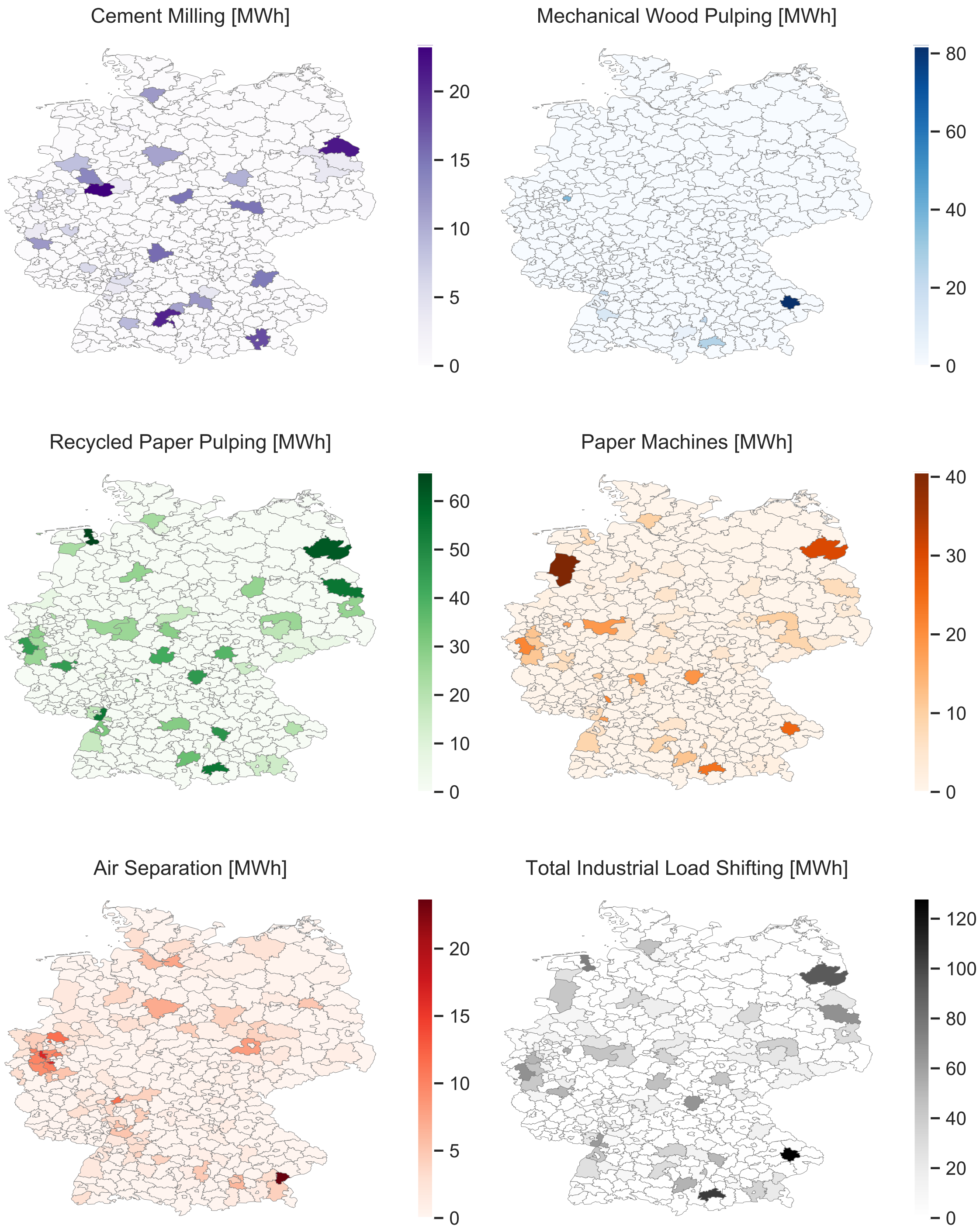

Figure 19: NUTS-3 annual average energy storage capacity

Table 15 compares the NUTS-0 energy storage capacity results with those from the reviewed literature. The total NUTS-0 annual average estimated energy storage capacity potential in this work is 2682 MWh. Paulus and Borggrefe (2011) and VDE (2012) estimate storage capacity based on the total product storage capacity of the plants. Klobasa (2007) reports total annual shiftable energy, meaning the shiftable load multiplied by Δt and number of allowable shifting interventions in a year; the figures for Klobasa (2007) shown in Table 15 are self-calculated by simply excluding the number of allowable shifting interventions in a year.

The wide range of values in Table 15 again demonstrates the significant disparity between different studies. The difference between Klobasa (2007), the current work, and Paulus and

Borggrefe (2011) and VDE (2012) can be explained in part by the differing methodologies; if the energy storage capacity is defined as the maximum possible product storage capacity, it would be expected to be greater than if defining the energy storage capacity as being limited by a certain intervention time. The results of the current work are 40-75% less than the results of Klobasa (2007), but this is a direct result of the lower decreasable load determined by the current work compared to Klobasa (2007) (see Table 14).

Table 15: NUTS-0 energy storage capacity [MWh] comparison across literature

	Cement Mills	Mechanical Wood Pulp	Recycled Pulp	Paper Machines	Air Separation
Klobasa (2007)	540	800	-	-	680
Paulus and Borggrefe (2011)	3014	468	-	-	-
VDE (2012)	29000	1300	-		-
Gruber et al. (2014)	-	-	-	-	-
Gils (2015)	-	-	-	-	-
Müller and Möst (2018)	-	-	-	-	-
Current work	308	209	1251	526	388

Load Shifting Potential Envelopes

Figure 20 depicts the annual NUTS-0 time series for $L(t)$, and the power and energy envelopes for the different load shifting applications. The scheduled load and power and energy envelopes for all applications except for cement milling are constant. As described in Section 3.2.3, cement milling $L(t)$ is modelled under the methodology that the cement mills in a particular NUTS-3 region shut down their operations during months where the average temperature in that NUTS-3 region is less than or equal to 1.4°C. From Figure 20, it can be seen from the scheduled load curve that the greatest number of plants are shut down in January, with a decreasing number of closed plants in February and December. From March to November, all of the cement mills are operating.

$P_{max}(t)$ for cement is the highest during the winter months when $L(t)$ is the lowest, and the inverse is true for $P_{min}(t)$. The plants in winter shutdown are theoretically able to ramp-up their cement mills from zero load to maximum capacity, if prior to the winter shut-down the cement clinker storage is filled to as high as capacity as possible, and there is free cement storage capacity; however, it must be noted that this would be logistically difficult to carry out, and also could only be requested for a limited total duration of time during the winter shut-down as a result of the limitations of cement clinker and cement storage capacities. The storage capacity for cement load shifting applications is the lowest during the winter shut-down months because the load is lower, and the permitted duration of decreased load (Δt) is unchanged.

The power envelope subplot of Figure 20 shows that $P_{min}(t)$ is generally greater than $P_{max}(t)$ for a given application. This is a result of relatively high utilization rates; industrial process applications run at a load in the proximity of maximum capacity, which means they have a more limited ability to increase the load in comparison to decreasing the load. In the case of cement milling, paper machines, and air separation, the minimum allowable load is limited due to f_{dec}, which consequently limits $P_{min}(t)$.

Overall, from Figure 20, it is clear that on a NUTS-0 basis, recycled paper pulping offers the highest negative balancing power, and outside of the cement winter shut-down period, recycled paper pulping and air separation plants offer the highest positive balancing power. Of course, from Figure 17 and 18, the relative potential varies between NUTS-3 regions. Recycled paper pulping also offers the highest storage capacity. These results indicate that despite not typically being considered as a viable load shifting application, recycled paper pulping has valuable potential, and should be pursued. With a combination of mechanical wood pulping, recycled paper pulping, and paper machines potentially all at one plant location, paper mills are a valuable source of load shifting potential.

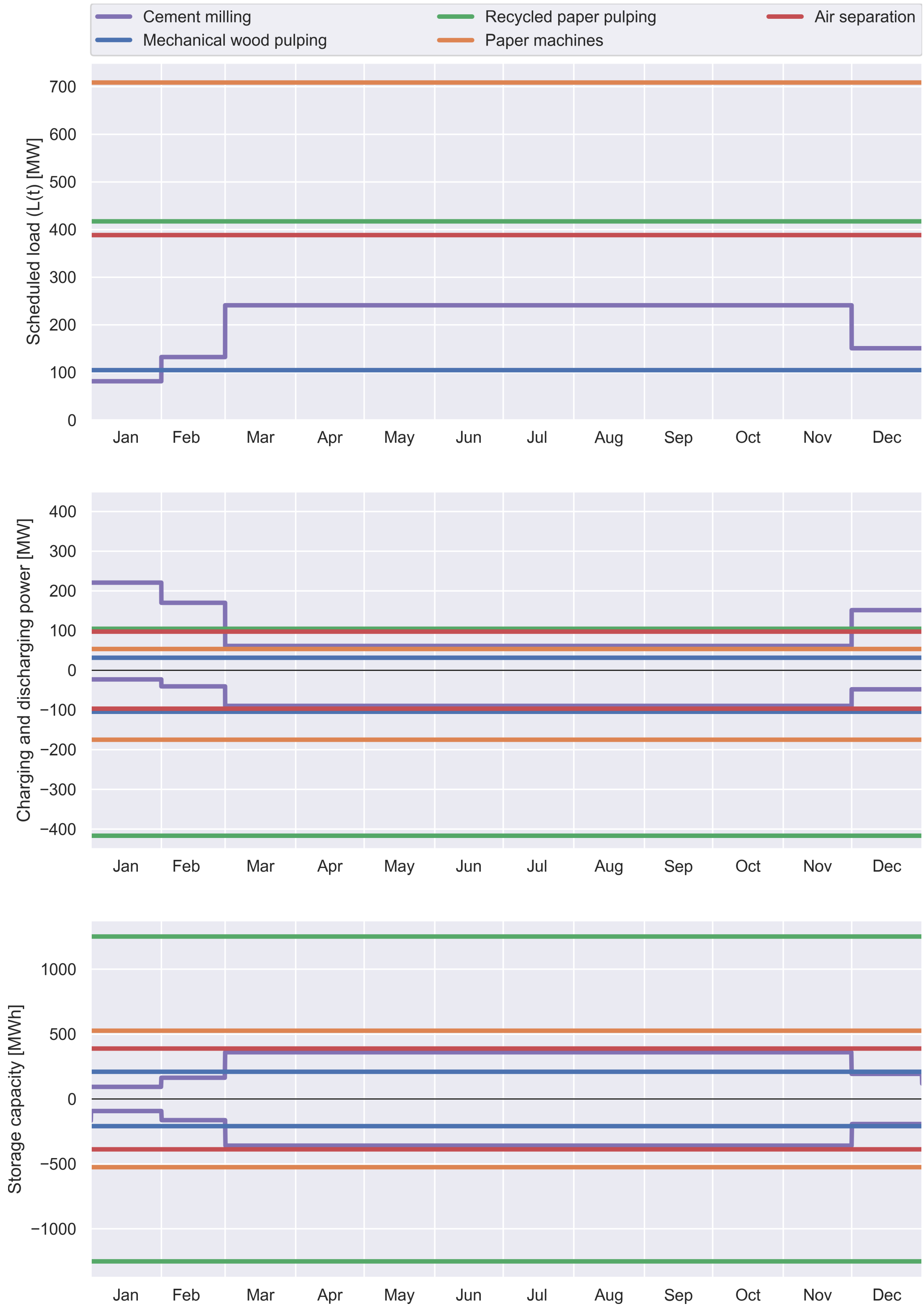

Figure 20: NUTS-0 scheduled load (top), power envelopes (middle), and energy envelopes (bottom) annual time series

4.2.2 Industrial Process Heat

In this section, the load shifting potential results for industrial PH applications are presented. As discussed in Section 3.3, in the PH load shifting potential analysis, the entire aggregated PH demand is considered, with no distinctions made between different temperature levels, or PH which is currently provided by electrical or fossil fuel generation. The aim of the analysis is to provide a preliminary idea of the scale of PH load shifting potential in comparison to the industrial processes investigated, as well as the associated NUTS-3 distribution. The complete set of input data, Python scripts, and output data can be accessed from the online repository.

Positive and Negative Balancing Power (P_{max} and P_{min})

As outlined in Section 3.3, different f and Δt values are tested for PH using the load shifting model, and the results compared to the potential estimated for the industrial processes. In order to compare potential, annual average NUTS-0 $P_{max}(t)$, $P_{min}(t)$, and energy storage capacity were calculated from the NUTS-3 branch specific power and energy envelope time series. Table 16 and Table 17 show the results for $P_{max}(t)$ and $P_{min}(t)$ respectively, with f ranging from 1%-5%. The industrial branch with the highest potential is highlighted in green, and with the lowest potential is highlighted in yellow. From Equation 9, $P_{max}(t)$ and $P_{min}(t)$ are dependent only on f, and not Δt.

Table 16: NUTS-0 annual average process heat $P_{max}(t)$ potential [MW] with f

	$f = 1\%$	$f = 2\%$	$f = 3\%$	$f = 4\%$	$f = 5\%$
Metal	22	44	66	87	109
Chemical and petrochemical	43	85	128	171	213
Minerals	33	67	100	134	167
Mining and quarrying	3	6	9	13	16
Food, beverages, and tobacco	45	90	136	181	226
Textile and leather	2	5	7	10	12
Paper, pulp, and printing	41	81	122	162	203
Transport equipment	3	6	9	12	15
Machinery	6	12	18	24	30
Wood and wood products	5	9	14	19	23
Other	16	32	49	65	81
Total	219	438	657	876	1095

The total annual average NUTS-0 $P_{max}(t)$ potential for industrial processes (refer to Table 12) is 376 MW, with a range for the individual applications of 31-104 MW. Comparing these values with Table 16, the total positive power balancing potential for PH applications exceeds the potential of industrial processes at $f = 2\%$. At the same time, the PH potential for the branches with lower potentials (ex. textile and leather) remain below the lowest individual industrial process application potential of 31 MW even at $f = 5\%$.

Table 17: NUTS-0 annual average process heat $P_{min}(t)$ potential [MW] with f

	$f = 1\%$	$f = 2\%$	$f = 3\%$	$f = 4\%$	$f = 5\%$
Metal	-138	-276	-414	-552	-690
Chemical and petrochemical	-123	-245	-368	-490	-613
Minerals	-56	-113	-169	-225	-282
Mining and quarrying	-3	-5	-8	-11	-13
Food, beverages, and tobacco	-38	-76	-114	-152	-190
Textile and leather	-2	-4	-6	-8	-10
Paper, pulp, and printing	-43	-86	-128	-171	-214
Transport equipment	-9	-17	-26	-34	-43
Machinery	-17	-34	-51	-68	-85
Wood and wood products	-8	-16	-24	-31	-39
Other	-14	-27	-41	-55	-68
Total	-449	-899	-1348	-1798	-2247

The total annual average NUTS-0 $P_{min}(t)$ potential for industrial processes (refer to Table 14) is -871 MW, with a range for the individual applications of - 77-417 MW. In comparison with the PH $P_{min}(t)$ potential presented in Table 17, as in the case with $P_{max}(t)$, the total NUTS-0 negative power balancing potential meets the total potential for the industrial processes at f = 2%. At the same time, some individual branches such as textile and leather, mining and quarrying, and wood and wood products, have a comparatively low potential even at higher f. Overall, the total PH load shifting potential is very high, even at low flexibilization rates; if only 2% of the PH demand in Germany was flexiblized, the load shifting potential in terms of positive and negative power balancing would rival the potential estimated for industrial process applications. However, the PH potential for some individual branches is very high, while the potential in other branches is much lower.

It can also be observed from Tables 16 and 17 that the industrial branch with the highest average $P_{max}(t)$ and $P_{min}(t)$ potential are different. This is a result of different NUTS-0 average full load hours for the various branches. For example, from Table 10, the metal branch overall has the highest full load hours out of all the branches, and the food, beverages, and tobacco branch has one of the lowest. High full load hours translates to high capacity utilization, which means that the free capacity ($P_{max}(t)$) is low, while the decreasable load ($P_{min}(t)$) is high. With lower capacity utilization, the relative $P_{max}(t)$ is higher, while $P_{min}(t)$ is lower. The nature of different industrial branches offering significantly different levels of $P_{max}(t)$ and $P_{min}(t)$ potential points to the importance of targeted PH load shifting development in the future.

Figure 21 presents the NUTS-3 distribution of annual average $P_{max}(t)$ and $P_{min}(t)$, assuming f = 2%. Energy storage capacity is not shown here because the distribution is identical to that for $P_{min}(t)$, as from Equation 6, $E_{max}(t)$ and $E_{min}(t)$ are proportional to $P_{min}(t)$. The average $P_{min}(t)$ potential in Figure 21 are presented without the negative sign to facilitate easier comparison between $P_{max}(t)$ and $P_{min}(t)$.

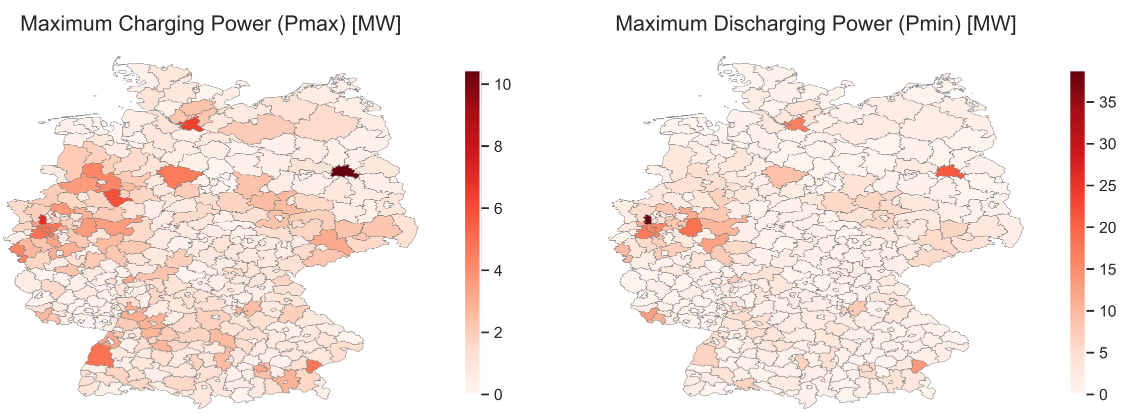

Figure 21: NUTS-3 annual average process heat $P_{min}(t)$ and $P_{max}(t)$ [MW], with f = 2%

In the same way as Tables 16 and 17, the distribution of $P_{max}(t)$ and $P_{min}(t)$ potentials in Figure 21 are different from each other. This is as a result of different compositions of the industrial branches within each NUTS-3 region; if an individual NUTS-3 region has a high number of employees of a branch, or branches with high full load hours, the $P_{max}(t)$ potential of this region will be comparatively high, while the $P_{min}(t)$ potential will be low, with the opposite being true for NUTS-3 regions with a high number of employees in low full load hour branches.

Figure 21 indicates that there is a pronounced concentration of load shifting potential, in particular $P_{max}(t)$, in the west region of Germany, although it is not restricted to the Ruhr region. It also shows a particularly high $P_{max}(t)$ potential in Berlin, and particularly high $P_{min}(t)$ potential in Duisburg.

Energy Storage Capacity (E_{max} and E_{min})

While $P_{max}(t)$ and $P_{min}(t)$ do not depend on Δt, the energy storage capacity $E_{max}(t)$ and $E_{min}(t)$ does. Table 18 shows the total NUTS-0 annual average energy storage capacity potential results for f ranging from 1%-6%, and Δt ranging from 1-6 hours. Combinations for which the energy storage capacity is lower than the total NUTS-0 average energy storage capacity for industrial processes (refer to Table 15) of 2682 MWh are highlighted in red, whereas the combinations resulting in a higher energy storage capacity are highlighted in green. It should be noted here that the results in Table 18 represent both $E_{max}(t)$ and $E_{min}(t)$, as when averaged of a year the result for both is the same, with the exception of the negative sign for $E_{min}(t)$ by convention.

Table 18: NUTS-0 annual average process heat energy storage capacity potential [MWh] with Δt and f

	$f = 1\%$	$f = 2\%$	$f = 3\%$	$f = 4\%$	$f = 5\%$	$f = 6\%$
$\Delta t = 1$ hrs	449	899	1348	1798	2247	2696
$\Delta t = 2$ hrs	899	1798	2696	3595	4494	5393
$\Delta t = 3$ hrs	1348	2696	4044	3593	6741	8089
$\Delta t = 4$ hrs	1798	3595	5393	7191	8988	10786
$\Delta t = 5$ hrs	2247	4494	6741	8988	11235	13482
$\Delta t = 6$ hrs	2697	5393	8090	10786	13483	16179

The results in Table 18 shows that there is a fairly limited range under which the PH energy storage potential is lower than the energy storage potential for industrial processes. At $\Delta t \geq 6$ hours, and $f \geq 6\%$, the PH energy storage capacity meets the capacity of industrial processes regardless of what f or Δt is - as long as it is greater than 1% or 1 hr. As mentioned in Section 2.3, Δt is entirely dependent on the heat load, and thermal energy storage size, and as such could have a wide range of values. As an example, taking the thermal storage capacity of the smallest storage unit installed in a district heating system in Germany listed by Christidis et al. (2017) of 140 MWh, and PH heat load of 10 MW (Schmidt, 2011), Δt would be 14 hrs.

Load Shifting Potential Envelopes

Figure 22 shows the total (sum of all industrial branches) NUTS-0 weekly time series for PH $L(t)$, $P_{max}(t)$ and $P_{min}(t)$, and $E_{max}(t)$ and $E_{min}(t)$, assuming $f = 2\%$ and $\Delta t = 4$ hrs. Under the assumptions of the PH load profiles used in this work from Gils (2015), there is no seasonal dependency for PH demand, and therefore the same weekly cycle repeats continuously throughout the year.

Figure 22 demonstrates the time dependence of the modelled PH scheduled load and corresponding load shifting potential. An increasing and decreasing cycling pattern can be seen between weekdays and weekend. From Figure 13, the load for all full load hour classes decreases on the weekend, with many of them dropping to zero load. This results in the weekly drop in scheduled load at the end of the week. There is also a daily variation in load for the lower capacity utilization full load hour classes, as can be seen in Figure 13. From Figure 22, the overall impact of this daily load variation on the aggregate load profile and power and energy envelopes is significantly less pronounced than the weekly variation. The PH load profiles used in this work, taken from Gils (2015), do not account for any seasonal variation.

With most industries having seasonally independent operation, a large seasonal impact on PH demand is not expected; however, it is possible that colder temperatures during the winter may result in increased thermal losses, resulting in a slightly increased demand over the winter months.

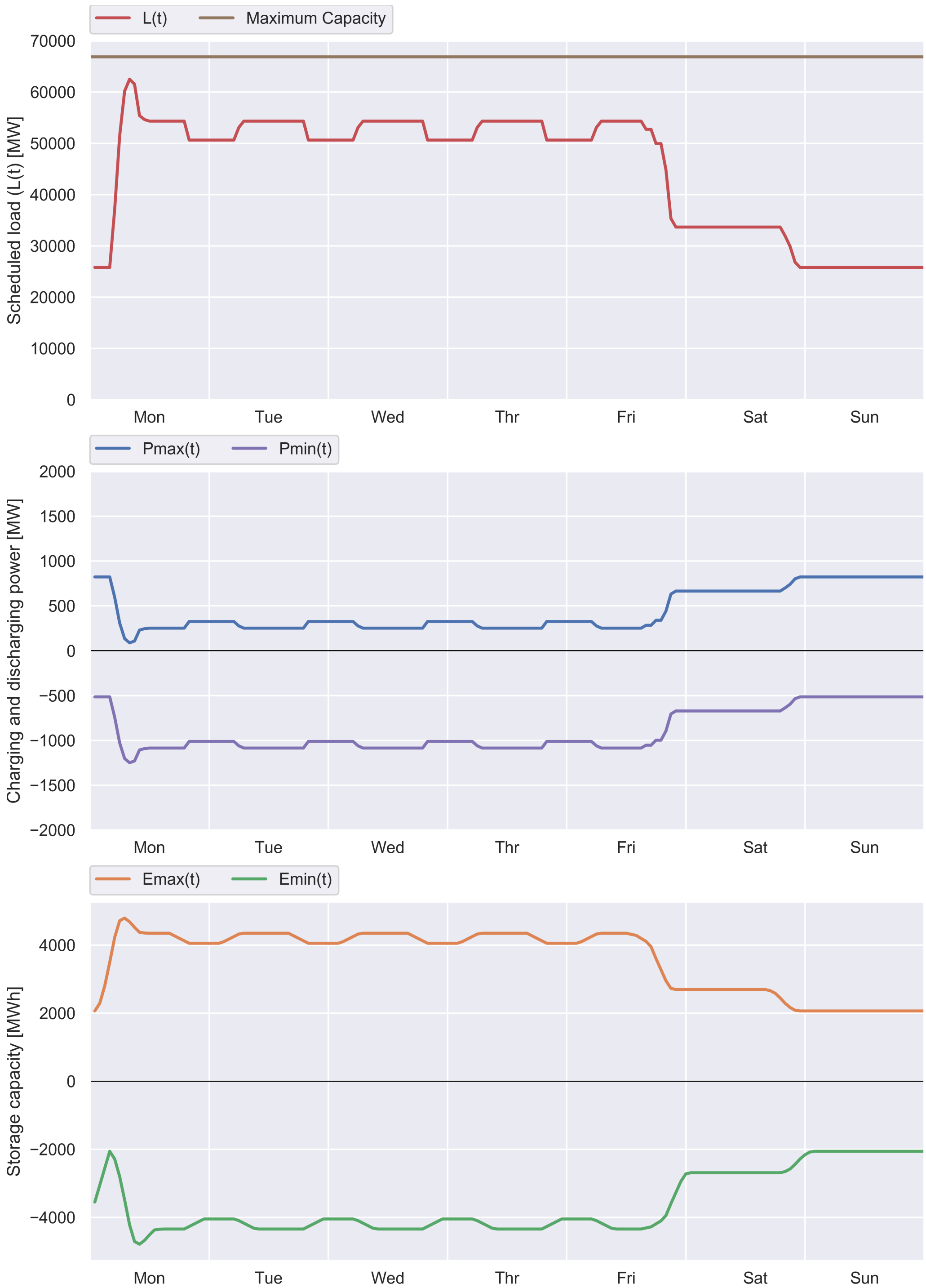

Figure 22: NUTS-0 process heat scheduled load (top), power envelopes (middle), and energy envelopes (bottom) weekly time series, with $f = 2\%$ and $\Delta t = 4$ hrs

In comparison with the industrial processes time-resolved load shifting potentials presented in Figure 20, the PH load shifting potential has a greater degree of time dependency. Whereas the industrial processes analyzed in this work are individual, high energy-intensity and capacity utilization industries, a broad range of PH applications are considered. The broader range of PH industries brings with it a wider range of capacity utilization characteristics and operation patterns.

4.3 Future Projections

Figure 23 shows the development of NUTS-0 production and specific electrical energy demand in Germany over the years from 1995 to 2018 for cement, mechanical wood pulp, recycled paper, paper, and air separation. Note that the temporal extent of the data is more limited for cement and air separation due to data availability. Using the historical developments shown in Figure 23, future projections of NUTS-0 industrial processes load shifting potential up to 2050 are made. The complete collection of input data, Python code, and output data can be accessed from the online repository.

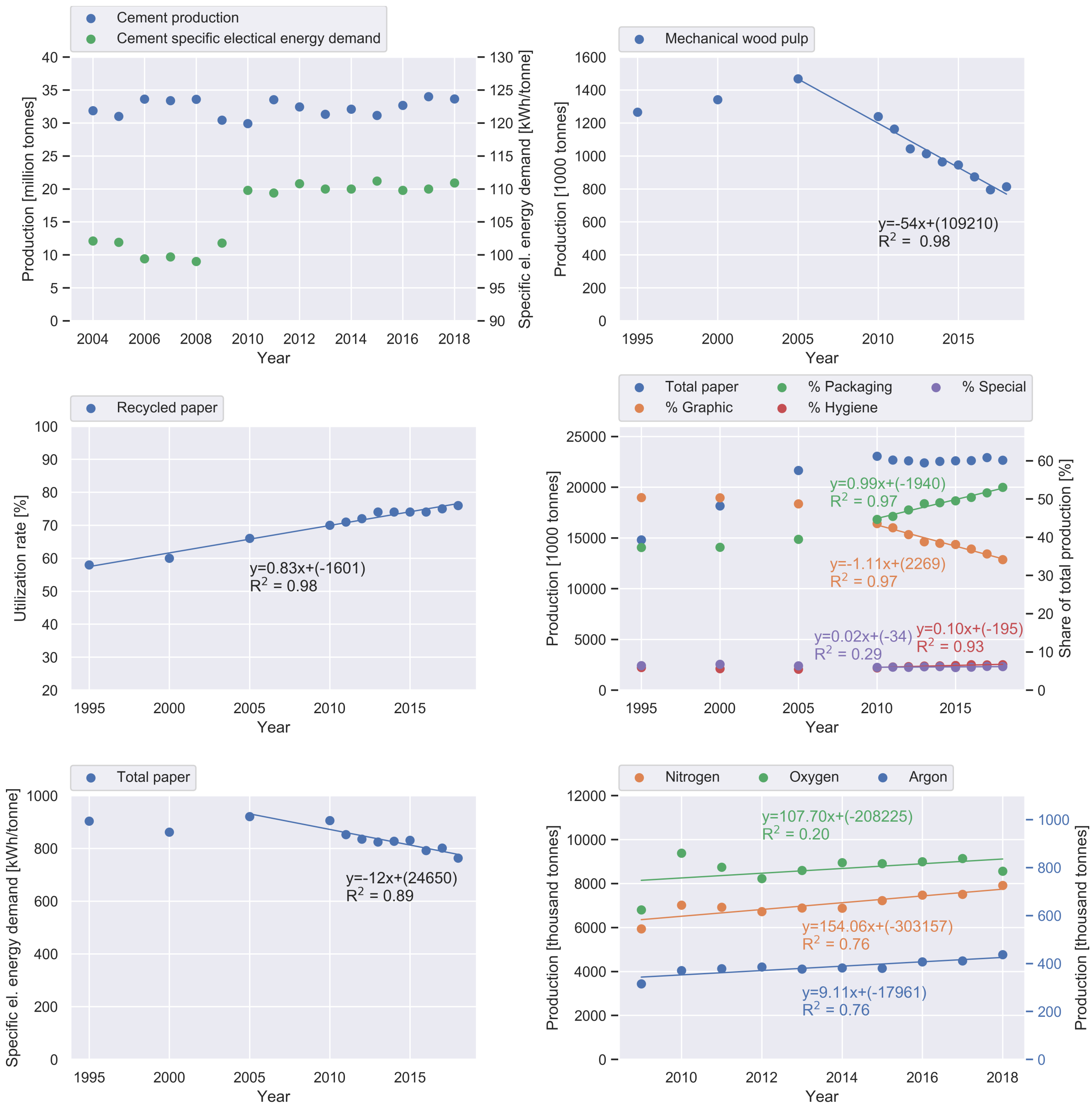

Figure 23: Historical production, specific electrical energy demand, and recycled paper utilization rate (own production with data from VDZ (2019a, 2014); VDP (2019c); Statistisches Bundesamt (2019a))

The top left subplot in Figure 23 shows that cement production in Germany has varied between approximately 30 and 35 million tonnes a year over the past 15 years, with no clear trend. In addition, it can be observed that the specific electrical energy demand has been hovering relatively constantly at approximately 110 kWh/tonne since 2010, after a sharp increase from 2008. The main reason for the higher specific energy demand over more recent years is an increase in demand for more finely ground cement (VDZ, 2019a). The specific electrical energy demand reported here is for the entire cement production process rather than cement milling alone, but as the increase in specific energy demand was a result of increase in demand for the milling process, and has remained unchanged since, it is be inferred that the energy demand for the milling process has remained unchanged since 2010. From these observations, it is assumed that cement production and specific electrical energy demand will not change between 2018 and 2050.

The top right subplot of Figure 23 shows that the production of mechanical wood pulp in Germany has been decreasing at a rate of approximately 54 thousand tonnes a year since 2005. However, if mechanical wood pulp production were to continue to decrease at this rate, production would reach zero in 2032. As virgin pulp is always needed as input into the paper production, complete closure of all mechanical wood pulping operations in Germany does not appear to be a likely future outcome. From additional pulp production and import data from VDP (2019c), there is no clear substitution of mechanical wood pulp by other forms of virgin pulp such as imported mechanical pulp, or produced or imported chemical pulp. In addition, wood pulp production did not decrease from 2017 to 2018, the first instance of this since 2005; this indicates that mechanical wood pulp production may be stabilizing. For these reasons, it is assumed that mechanical wood pulp production will remain at 2018 levels through to 2050.

In regards to recycled paper pulping, the middle left subplot of Figure 23 shows that the recycled paper utilization rate (the quantity of recycled paper pulped as compared to the quantity of paper produced) has been increasing at an average rate of 0.83% per year since 1995, with a high coefficient of determination of 0.98. If it continues to increase at the same rate, by 2050 the recycled paper utilization rate will be 103%. A utilization of rate of 103% has already been achieved and surpassed by some countries such as Denmark, Croatia, and Ukraine (VDP, 2019c), thus a utilization rate of this magnitude is theoretically achievable. Therefore, it is assumed that the recycled paper utilization rate will continue to follow the same linear trend forward to 2050, and the quantity of pulped recycled paper will be estimated using the future projected total paper production.

The middle right subplot of Figure 23 shows the history of total paper production since 1995, as well as the relative shares of graphic paper, packaging paper, hygiene paper, and special & technical paper production. Knowing the production development for each type of paper is important, as the specific electrical energy demands used in this work (refer to Table 7) are dependent on the paper type.

It is evident that the quantity of total paper produced has remained relatively constant since 2010, but the production of individual paper types has been changing, graphic and packaging paper in particular. The production of packaging paper has been on a upward trend, while the production of graphic paper (newsprint, printing, and writing papers) has been on a downward trend. As a result of anticipated continued increases in online retailing and movement towards more paper based packaging, as well as decreasing graphic paper production as a result of ongoing digitalization, both of these trends are expected to continue (VDP, 2019c). The relative shares of hygiene and special & technical paper production have on average been increasing slightly since 2010, filling the gap between graphic paper production decrease, and packaging paper production increase. However, if the decrease in graphic paper production continues at the same rate, it will drop to zero by 2049. At present, it seems unlikely that technology will so completely replace graphic paper in all areas, therefore a more conservative approach for the purpose of the future projections is taken. It is assumed here that the paper production trends from 2010-2018 will continue until 2030, where graphic paper is estimated to comprise 21% of total paper production, and packaging paper 65%, and then will stay constant between 2030 and 2050.

The bottom right subplot of Figure 23 shows the development of the specific electrical energy demand for paper production since 1995. Note that this energy demand is for the entire paper production process rather than for the individual process steps of mechanical wood pulping, recycled paper pulping, and paper machines considered in this work. The data depicts an overall decreasing trend in specific electrical energy demand since 2005. However, it is too difficult to attribute this trend directly to energy efficiency improvements in the individual process steps considered in this work, especially considering that there may be other factors contributing to the decreasing specific electrical energy demand. For example, the decreasing rate of mechanical wood pulp production since 2005 may play a role. Mechanical wood pulping has a high electrical energy demand, and if the mechanical wood pulp is substituted by less electrical energy intensive pulp such as recycled paper pulp, chemical pulp, or imported pulp, then it would decrease the observed overall specific energy demand for paper production in Germany without any changes in the specific energy demand of the individual process steps themselves. The substitution of graphic paper production by lower energy intensive packaging paper production would have a similar effect. For these reasons of uncertainty regarding the interpretation of the available data from VDP (2019c), the annual rates of decrease in specific electrical energy demand from Gils (2015) is adopted: 0.3% for mechanical wood pulping and paper machines, and 0% for recycled paper pulping.

The production of air separation gases nitrogen, oxygen, and argon have been on an overall increasing trend since 2009, although the coefficients of determination are significantly lower than for the paper products. Despite the less ideal linear correlations, with a lack of further information, the approximated linear trends for air separation will be assumed to continue into the future. In regards to the specific electrical energy demands, the assumed annual decrease of 0.3% from Gils (2015) is adopted.

Table 19 summarizes the assumed future developments in production and specific electrical energy demand for industrial process applications used in the estimations of load shifting potentials to 2050.

Table 19: Developments in annual production and specific electrical energy demand assumed for estimations of future load shifting potential. [1]Gils (2015)

	Future annual production	Δe_i/year
Cement mills	±0 tonnes/year	±0%
Mechanical wood pulp	±0 tonnes/year	-0.3%[1]
Recycled paper pulp	Utilization [% total paper production] determined according to 1995-2018 linear trendline	±0%[1]
Total paper production	±0 tonnes/year	-
Graphic paper machine	Share of total paper production determined according to 2010-2018 linear trendline until 2030.	-0.3%[1]
Packaging paper machine	Share of total paper production determined according to 2010-2018 linear trendline until 2030.	-0.3%[1]
Hygiene paper machine	Share of total paper production determined according to 2010-2018 linear trendline until 2030.	-0.3%[1]
Special/technical paper machine	Share of total paper production determined according to 2010-2018 linear trendline until 2030.	-0.3%[1]
Oxygen separation	According to 2009-2018 linear trendline	-0.3%[1]
Nitrogen separation	According to 2009-2018 linear trendline	-0.3%[1]
Argon separation	According to 2009-2018 linear trendline	-0.3%[1]

Figure 24 depicts the estimated developments in load shifting potential for industrial processes from 2018 to 2050, along with the 95% prediction intervals reflecting uncertainties in the historical production trends.

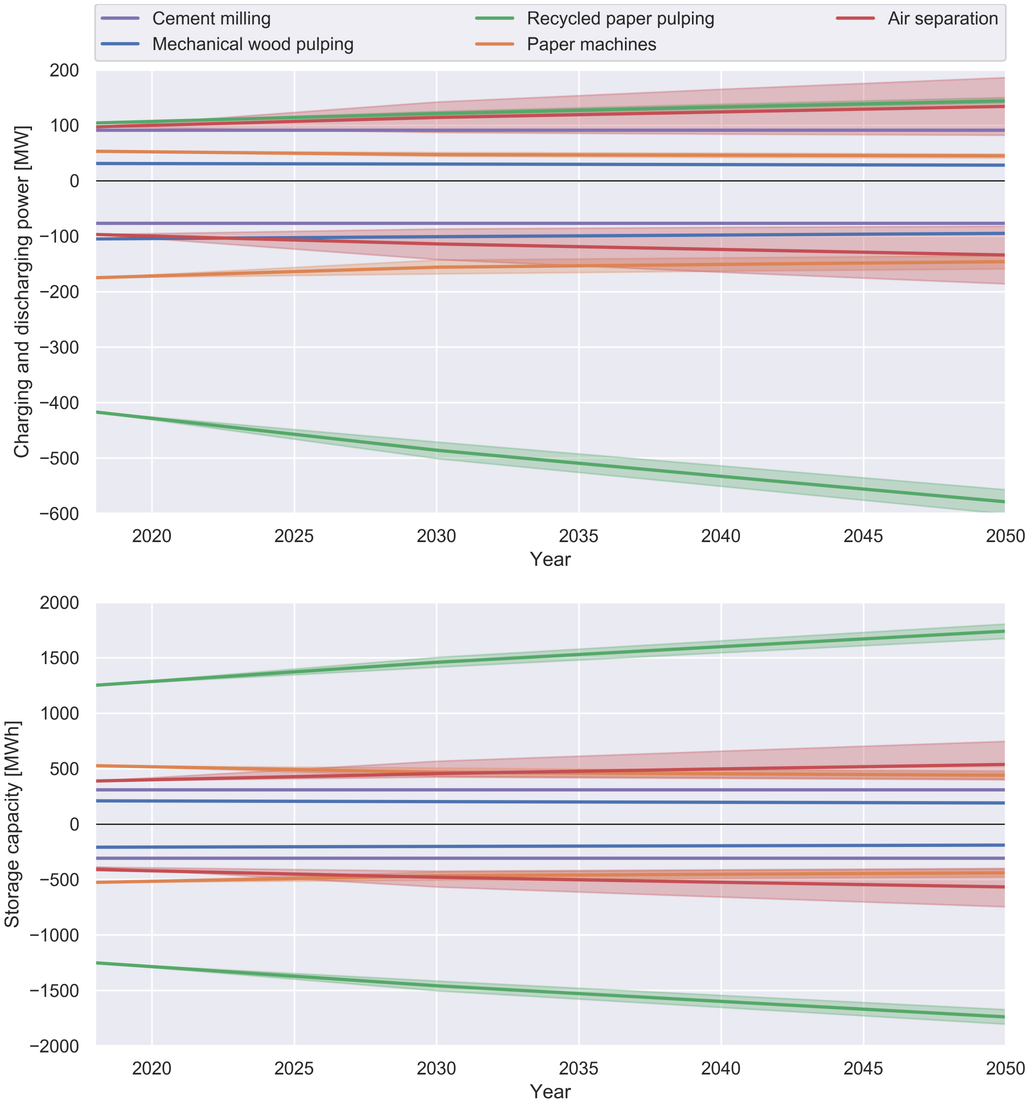

Figure 24: Projected future development of industrial processes annual average load shifting potential

What stands out in particular from Figure 24 is the large projected increase in recycled paper pulping potential, which is a result of the assumed continuation of increase in recycled paper utilisation. In comparison to recycled paper pulping, the changes in potential of the other applications do not appear as significant, but an increase in air separation load shifting potential as well as decrease in paper machine potential is observable. The load shifting potential for paper machines is projected to decrease mainly due to the substitution of higher energy intensive graphic paper production with lower energy intensive packaging paper production, while air separation load shifting potential increases as a result of projected increases in production. The load shifting potential for mechanical wood pulping decreases slightly due to gradual production efficiency gains.

Overall, the total industrial processes NUTS-0 annual average $P_{max}(t)$ and $P_{min}(t)$ potentials are projected to increase 18% by 2050 to 443 MW and -1032 MW, respectively. The total average storage capacity is estimated to increase 20% to 3214 MWh by 2050.

It is important to note here that future projections are simply estimations based on a set of assumptions, and can model future developments with only limited accuracy. The projections made in this work are estimations based on past production and specific energy demand trends, however, at any point new circumstances can significantly alter industry development. In addition, several assumptions were made regarding future developments that diverge from the overall trends seen in the past years, such as regarding mechanical wood pulp and the relative production of different types of paper. Actual future industrial developments cannot be predicted with certainty. In particular, the likelihood of past production trends continuing unchanged decreases as time progresses, meaning that the estimations made for 2040 and 2050 are considerably weaker than the estimations made for 2030.

The future load shifting potential for industrial process heat applications is not estimated in this work, but it can be mentioned that Gils (2015) projected that the total industrial final energy demand would increase from 2009 to 2020, and then decrease through 2040 and 2050 to 90% of 2009 values in 2050. These projections were based on the results of an energy demand scenario by Teske et al. (2012). Under this projection, the theoretical industrial PH load shifting potential (not taking method of generation into account) would decrease in the future; however, electrically generated process heat is expected to increase, thereby increasing the accessible load shifting potential.

5 Summary and Conclusions

In this work, NUTS-3 time-resolved load shifting potential for industrial processes and process heat applications in Germany was modelled, with open access to all data, methodology, code, and results. The first aim was to determine whether NUTS-3 annual energy demand for industrial processes can be accurately estimated using an alternative method to the plant specific characterization method, using instead easily accessible data from statistical databases or industry associations. Three alternative methods were developed and tested; one which disaggregates NUTS-0 production data according to NUTS-3 employment data, one which disaggregates NUTS-0 electrical energy demand data according to NUTS-3 employment data, and one which compares NUTS-3 total industrial electrical energy demand to total electrical energy demand of industrial process load shifting applications.

It was found that none of three alternative methods are able to estimate NUTS-3 annual energy demand with sufficient accuracy in comparison to the plant specific characterization method. The main challenge with utilizing industrial NUTS-3 data available from statistical databases such as from Statistisches Bundesamt is the requirement for statistical confidentiality. As there are a relatively small number of industrial plants per NUTS-3 region, in order to be reportable, data categorization must be of a sufficiently broad scope to encompass enough plants to ensure confidentiality of the reported data. The broadness of available industrial NUTS-3 data limits the usefulness of the data for obtaining accurate information on relatively narrow subsets of industries, such as the industrial process load shifting applications investigated in this work. It is thus concluded that the plant specific characterization method is necessary to adequately characterize NUTS-3 industrial process load shifting applications.

As plant specific data used by previous studies (Gruber et al., 2014; FfE, 2016) has not been made accessible, the plant specific characterization method was carried out for the purposes of estimating NUTS-3 load shifting potential for industrial processes in this work. In the execution of the plant specific characterization method, a dataset of the locations and production of cement milling, mechanical wood pulping, recycled paper pulping, and paper machine operations in Germany was produced using information obtained from publicly accessible online sources, and has been made openly accessible for future reference and use. Air separation plants were not able to be characterized due to the lack of available consolidated list of plants from an industrial association or other source. It is noted that the accuracy of the data gathered using the plant specific characterization method is also not perfect due to potentially outdated sources, use of estimation methods for locations where the desired data could not be found, and reliance of an assumed capacity utilization to convert production capacity to production. Nonetheless, the total NUTS-0 application specific annual production obtained using the plant specific characterization method compares well with reported NUTS-0 production by industrial associations, with 1.3-6.8 % difference. Annual electrical energy demand is estimated from the collected production data using specific electrical energy demand obtained from previous studies and industry sources.

The NUTS-3 annual energy results from the plant specific characterization method are then used with a time-resolved load shifting model previously developed by Kleinhans (2014), and model inputs Δt, s_{util}, f_{inc} and f_{dec}, and load profiles adapted from literature and industry sources to estimate NUTS-3 load shifting potential. Annual energy results from the allocation of NUTS-0 production method were used in place of the plant specific characterization method for air separation plants. The total NUTS-0 annual average positive balancing power, negative balancing power, and energy storage potential is estimated to be 376 MW, -871 MW, and 2682 MWh respectively.

The second research question that was investigated is how the resulting load shifting potential of industrial processes compare with the results of other studies. It was found that it is difficult to compare the NUTS-3 results of the current work with other studies because there are so few existing industrial NUTS-3 DR studies, and those which were found do not make the numerical results accessible. However, a visual comparison of the NUTS-3 application specific annual energy demand produced in this work with NUTS-3 maps from Gruber et al. (2014) revealed similar distributions. To evaluate the absolute value of the load shifting potential estimations, NUTS-0 results were compared with other results across literature. The results of the current work are overall lower than the results of previous studies, however not without reason. Overall, it is difficult to conclusively verify or reject the results of the study against literature due to the large range of results in the reviewed studies, as well as the dependency of load shifting potential estimations on model inputs such as e_i, s_{util}, f, and Δt which also have a wide reported range in literature, and for which it is difficult to establish which most accurately represents reality.

The third research goal was to do a preliminary investigation of NUTS-3 process heat load shifting potential, and compare the PH potential with the potential of industrial processes. A method adapted from Gils (2015) was used to estimate NUTS-3 PH annual energy demand, and determine corresponding maximum capacity and select load profiles. As no proposed time frame of management or flexible component were identified in the reviewed literature, different Δt and f were tested. It was found that the PH load shifting potential is high in comparison to the industrial processes; with a flexible component of just 2%, the total NUTS-0 PH positive and negative power balancing potential meets and exceeds that of industrial processes. The storage capacity potential is dependent on Δt and f, but it is found that the estimated energy storage potential of industrial processes can be met with as low as f=1% and Δt=6 hrs, or Δt=1 hrs and f=6%. In comparison to the industrial processes investigated it was also found that the NUTS-3 distribution of PH load shifting potential is more concentrated in the west region of Germany, and has a higher degree of time dependency.

In regards to the last research goal of estimating future load shifting potential for industrial processes, based on production and specific energy demand trends in recent history, total load shifting potential is projected to increase through to 2050. The increase in load shifting potential is caused by projected increases in recycled paper pulping and air separation, whereas the potential of the other applications is projected to remain constant or decrease. Total annual average NUTS-0 positive and negative power balancing potential are projected to increase 18% by 2050 to 443 and -1032 MW respectively, and storage capacity is estimated to increase 20% to 3214 MWh.

Supplementary Material

The Python scripts and corresponding input and output data can be accessed from https://doi.org/10.5281/zenodo.3613767.

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