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Matthias Rehfeldt

Fuel Switching as Contribution to the Decarbonisation of the Industry Sector

Integration in a Bottom-up Energy System Model

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Fuel switching as contribution to the decarbonisation of the industry sector

Integration in a bottom-up energy system model

Brandstofomschakeling als bijdrage aan de koolstofarme industrie

Integratie in een bottom-up energiesysteemmodel

(met een samenvatting in het Nederlands)

Proefschrift

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Promotoren:
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Winning? Is that what you think it's about? I'm not trying to win.
I'm not doing this because I want to beat someone [...].
God knows it's not because it's easy.
It's not even because it works, because it hardly ever does.
I do what I do because it's right! Because it's decent!
And above all, it's kind! [...].
Stand with me. [...]Maybe we can help a little.

Why not, just at the end, just be kind?

The Twelfth Doctor, BBC 2017.

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1. Introduction

1.1 Energy demand, fuel choice and the environment

1.1.1 The relevance of energy carrier choice

Energy is a key factor for the economic and social potential of societies. Easy access enables economic development, helps to satisfy basic needs and frees resources for cultural, social and scientific progress. Availability of energy is thus one of the main requirements for human civilization. For 2017, the world's primary energy demand was estimated to 162,500 TWh [1], after 116,600 TWh in 2000 and 97,500 TWh in 1990 [2]. The European Union (EU28) accounted for a primary energy demand of 17,750 TWh, after 19,000 TWh in 2000 and 18,000 TWh in 1990 [3]. Its final energy demand amounted to 12,883 TWh in 2016 [4] (Figure 1.1). The energy consumption per capita is unbalanced on a global scale. While an average human required about 18 MWh primary energy in 1990 and 22 MWh in 2016, a European required 35 MWh in 2016. It can therefore be expected that the global energy demand will increase further, if living standards of the global south are to rise. The manufacturing industry will continue to play a major role in developed and developing countries; industrialized countries may use a quarter or more of their energy supply in industry [4]. The most important industrial subsectors in this regard, called energy-intensive, are the iron and steel industry, non-metallic minerals, pulp and paper, non-ferrous metals, basic chemicals and sometimes food production. In the EU28, these sectors consume 75% of the industrial or 19% of the total FED (2410 TWh).

Fossil or fossil-based energy carriers mainly cover this energy demand. Worldwide, 81% of the primary energy demand are considered fossil-based [1], while the EU28 covered 72% of their primary energy demand with fossil fuels in 2016 [3] (Figure 1.1). Only 262 TWh (8%) of the final energy demand in industry is categorized as 'renewables' [4], with the mentioned energy-intensive industries reaching 188 TWh (8%). The use of solid fuels (mostly coal) and oil each declined by almost 50% since 1990 in these subsectors, while gas use (natural gas, derived gases) declined by 20%[1]. This can mostly be attributed to a strong increase in energy efficiency. However, energy efficiency is limited by thermodynamics and some processes already approach these limits [5].

1 In relative terms, natural gas maintained its market share on the FED of 31% between 1990 and 2016, while those of coal and oil declined from 37% to 22%.

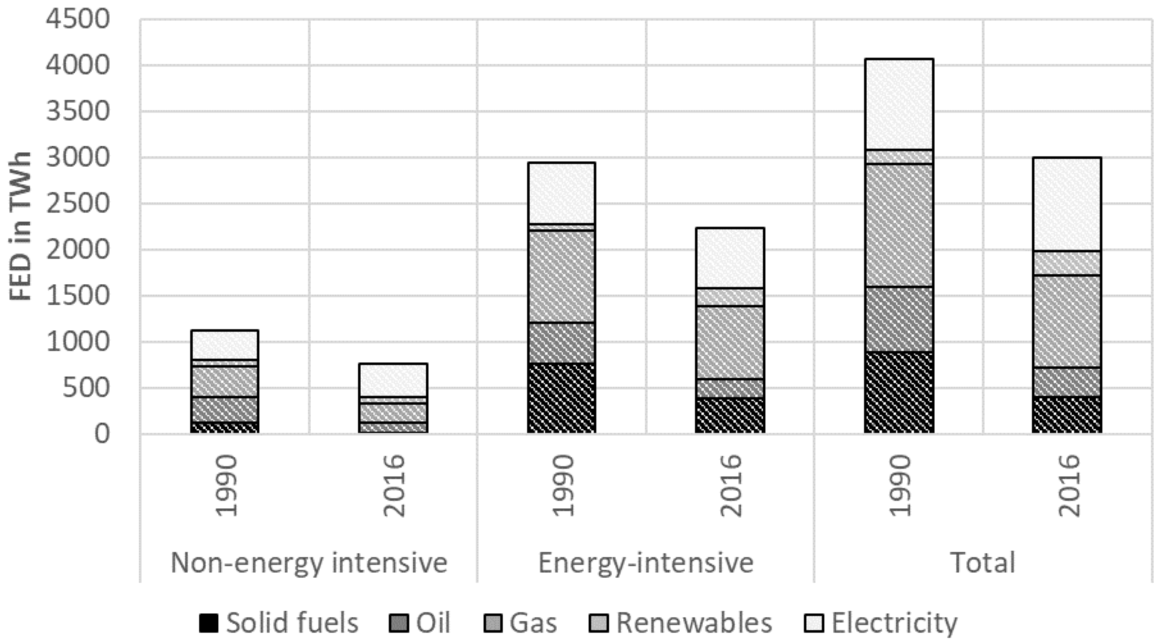

Figure 1.1: Development of final energy demand in the EU 28 manufacturing industry between 1990 and 2016. Source: [4]

The use of fossil fuels has consequences. The emission of greenhouse gases (GHG) caused, among other sources, by fossil energy use is the main driver for climate change [6]. In its special report on 1.5°C global warming, the IPCC highlights that the emissions already released to the atmosphere are unlikely to create further warming of more than 0.5°C in this century. Thus, determined action during the next three decades may limit global warming to 1.5°C above pre-industrial levels. While considerable uncertainties exist regarding the actually remaining carbon budget, the conclusions of the situation assessment are clear: This determined action must reduce worldwide GHG emissions by ~45% until 2030[2] and reach net-neutrality by 2050. The EU aims to reduce its GHG emissions by 40% until 2030 and reach net-neutrality in 2050 [7]. However, the EU uses the base year 1990 for this goal. Based on 2010, the EU's level of ambition equals a reduction of 30% until 2030 and is thus not compatible with IPCC's 1.5°C pathways. In the industry sector, although no targets have been defined on that level in the EU, an equivalent reduction would result in 21% GHG-emission reduction based on 2010 (Table 1.1) In Germany, the federal government aims to reduce overall GHG emissions by 55% until 2030. Also based on 1990, these reductions equal a 42% reduction compared to 2010. They are thus also short of the IPCC pathways, albeit closely. In addition to national targets, Germany has set sectoral targets [8]. Those demand a reduction of GHG emissions in the industry sector by 50% until 2030 compared to 1990. Due to the comparably high reduction in industry between 1990 and 2010, this equals a reduction of 23% compared to 2010.

[2] Base year 2010.

Table 1.1: Comparison of emission reduction targets of Germany, the EU and 1.5°C pathways of the IPCC with differing base years

Industry		*1990*	*2010*	*2015*	*Target 2030*
Sectoral target Germany	Absolute Emissions [$Mt_{CO2-eq.}$]	279	185	185	<143
	Reduction (1990)	-	34%	34%	>49 %
	Reduction (2010)	-	-	0%	23%
EU industry	Absolute Emissions [$Mt_{CO2-eq.}$]	1118	850	792	671
	Reduction (1990)	0	24%	29%	40%
	Reduction (2010)	-	-	7%	21%
IPCC 1.5°C pathway (broken down to German industry)	Absolute Emissions [$Mt_{CO2-eq.}$]	279	185	185	102
	Reduction (1990)			34%	64%
	Reduction (2010)	-	-	0%	45%

Thus, while the overall target of GHG-neutrality until 2050 (deep reduction) is necessary in 1.5°C pathways and a set goal for the EU28 and Germany, intermediate targets aiming for fast reductions until 2030 seem insufficient. However, these are just as important, since not the rate but the sum of GHG released into the atmosphere (i.e. the carbon budget) determines global warming. The concept of a carbon budget highlights this relation. The remaining carbon budget is the cumulative amount of CO_2-emissions that may be released to the atmosphere and remain below given temperature increase thresholds, in this case 1.5°C. And although substantial uncertainties exist, the carbon budget is estimated to range between 420 and 840 $GtCO_2$ [9], which equals 9 to 22 years of current emissions[3]. For a 2°C-target, these values increase to between 1170 and 2030 $GtCO_2$, equalling 26 years and 52 years, respectively. The need for fast emission reductions is thus obvious.

An important and immediately available tool for fast reductions of GHG emissions is increased emission efficiency. In its broader sense, it describes the emissions generated to provide a given service (e.g. mobility, food, energy). This includes actions along the entire value chain, e.g. demand reduction, recycling, material efficiency, behavioural change of consumers, raw material substitution and others. Narrowed down to industrial energy use, emission efficiency can be improved by the reduction of energy losses (energy efficiency) or the use of less emission intensive energy carriers. Practically, this can be realized by the phase-out of fossil fuels and increased use of renewable energy sources (RES), especially renewable electricity. The process of doing so is called 'fuel switch' in

[3] With the uncertainty of current emissions between 39 and 45 GtCO2/a.

engineering and sustainability context and 'inter-fuel substitution' in economic and econometric context[4].

Quite generally, 'energy carrier' describes any physical form in which energy is stored or transported. Important examples are hard coal, fuel oil, electricity, biomass and natural gas. In a broad definition, it may also refer to a slab of steel, a bag of cement or a hot cup of coffee. However, in this thesis, the term energy carrier is limited to those included in the Eurostat energy balances [4]. Another term is 'fuel'. It describes material, which releases energy on combustion (e.g. wood or coal). It is thus a subset of energy carriers, excluding e.g. electricity. The terms 'fuel switch' and 'inter-fuel substitution' thus seem to exclude electricity as substitute for fuels, notably renewable energy sources (RES)[5]. However, as Stern [11] shows, electricity is often included in inter-fuel substitution analyses. A broader term could be 'energy carrier switch'. In this work, electricity is included in the terms 'fuel switch' and 'inter-fuel substitution'.

This thesis applies the Eurostat-definition of the industrial structure. It divides industrial activity ('sector') in 13 groups ('subsector'). Of those, six subsectors accounting for 70% of the energy demand are called 'energy intensive'. They are the focus of this research.

1.1.2 The rationale and the restrictions of fuel switching

Fuel switching describes the process of changing the energy carrier used to supply energy. It thus offers the opportunity to mitigate negative effects of energy supply without influencing the delivered service, similar to energy efficiency measures and in contrast to sufficiency measures, which aim to reduce the demanded service (Figure 1.2). In the context of the manufacturing industry, the 'service' is the product (e.g. flat glass) and its creation uses energy in form of process heat and mechanical work. In a broader, societal context, the 'service' might be defined differently, e.g. as 'mobility', supplied by cars and trains.

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4 The econometric term may stem from the classic definition of labour, energy and capital as substitutable production factors. Within this concept, energy carriers (e.g. coal, oil, gas) are generally interchangeable within the category 'energy'. The extent to which they actually are substitutes to each other (in the light of different prices and societal feedbacks) is subject of this research area.

5 *'energy from renewable sources' or 'renewable energy' means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas' [10]*

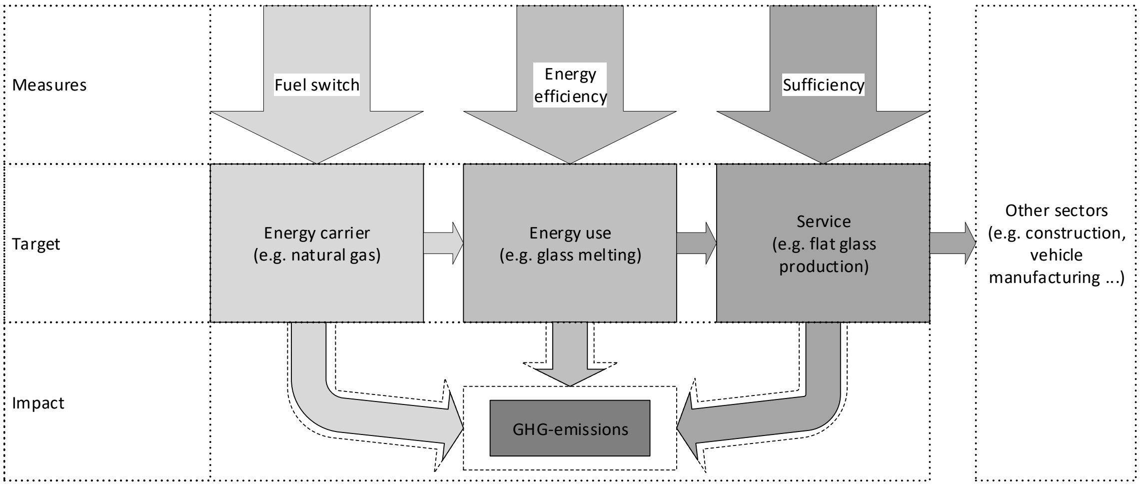

Figure 1.2: Fuel switching in relation to energy efficiency and sufficiency

In principle, fuel switching is therefore a soft tool, as it does not influence the service but merely the way it is supplied. However, depending on ambition, considerable effort is needed to realize fuel switching measures and in contrast to many energy efficiency measures, the no-regret potential [12] is limited[6]. However, similarities regarding the barriers to fuel switching and energy efficiency can be identified [14].

A fuel switch option towards less emission intensity is the replacement of coal and oil with natural gas, and it has been used in the past. In this case, the higher price for natural gas compared to coal was offset by its inherent advantages: good combustion properties, high availability and convenient logistic (where infrastructure is available). Additionally, fuel oil got more expensive, making the switch to natural gas an economic, rather than an ecologic, decision. In order to achieve further emission reductions, in particular those in line with 1.5°C global warming, however, other energy carriers must be considered. This includes biomass and electricity, if generated from sustainable sources. Both are currently niche options to supply process heat in the manufacturing industry. Positive examples are the use of cheap and easily available production residues in paper production and secondary steel production in electric arc furnaces (EAF) [15]. Both energy carriers may potentially provide low-emission energy. They do however face economic challenges due to their higher price. In the European Union, Electricity usually costs twice as much as natural gas for industry [16,17], (Figure 1.3). Biomass, while competitive with coal when available as production residue, is estimated to become more expensive if produced (and imported) as energy carrier. Figure 1.4 shows an estimate of the biomass potential available to the European industry and its price. The first price level is the biomass residue use in 2015. The second price level is domestic wood- and agriculture-based production. The last level is international traded biomass, e.g. pellets, with shipping costs from Russia or Canada as the main additional price component. As the majority of biomass used in industry

6 No-regret potentials of fuel switch away from fossil fuels include local and regional health benefits due to reduced pollutant emissions ([13]).

today consists of production residues, actual price levels of intensified biomass use are highly uncertain.

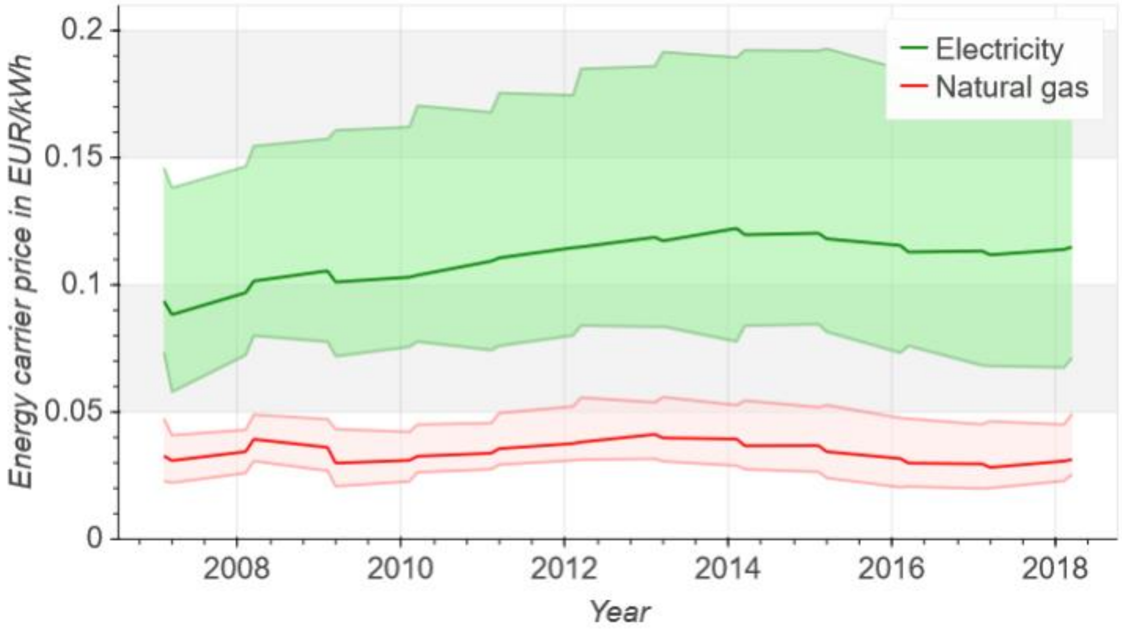

Figure 1.3: Electricity (band IC) and natural gas (band I3) prices for non-household consumers in EU28; range of price bands indicated by filled area. Source: [16,17]

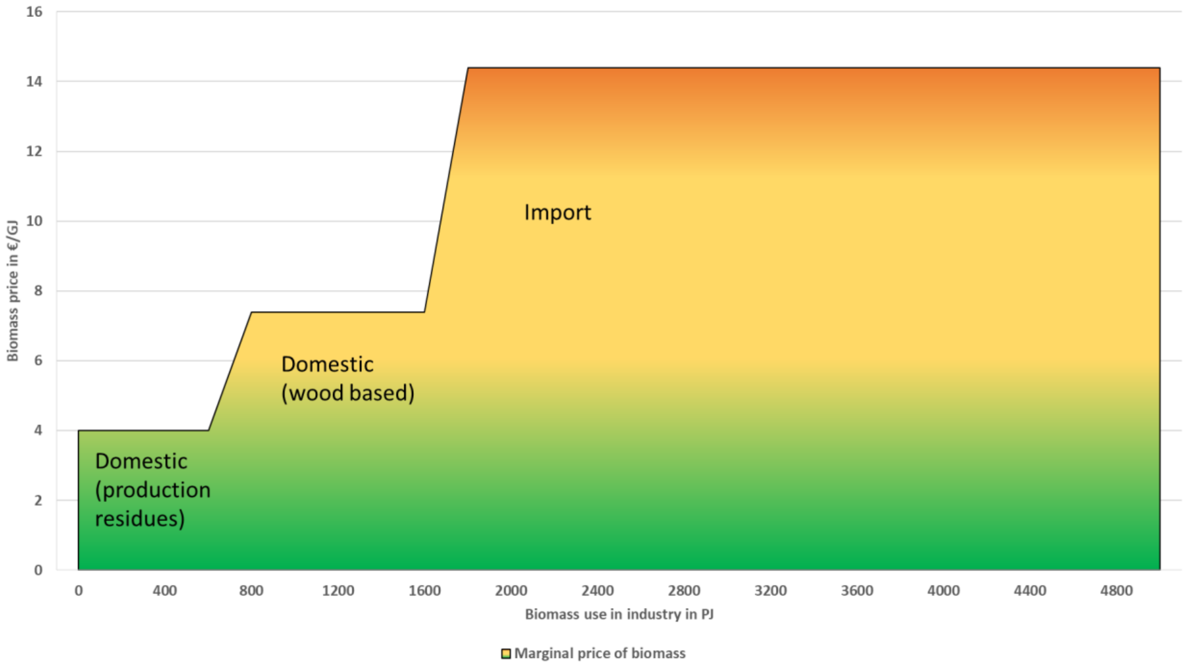

Figure 1.4: Potential-cost curve of biomass available to the EU28 industry sector. Source: [18]

Based on the required effort, three types of fuel switching can be identified: First, short-term measures with limited need for technological change (e.g. change of the burner in steam generation). These may include adding small amounts of biomass to coal-fired steam generation [19–21] or the use of synthetic methane based on renewable electricity instead of natural gas. These measures can create a flexible system with energy carrier changes on a daily basis during ongoing production. Second, modernization of existing process heating installations (and their infrastructure) to, partially or completely, replace the previous energy carrier. This increased effort might be necessary when the new fuel has greatly different physical properties (e.g. storage requirements or heating value).These measures are tied to maintenance cycles of up to ten years and include considerable investments. Third, extensive fuel switch measures require replacement of production sites or large parts thereof, especially in complex production processes that have their own energy system (e.g. integrated steel plants, refineries, basic chemicals). These measures can be tied to full reinvestment cycles of 30 or more years and require substantial capital and commitment.

The economic influences on fuel switching and its cost-effectiveness can be discussed with regard to large-scale shifts of energy use (e.g. shale gas use, 70's oil crisis, dash for gas in the UK during the 1990s) or on a process or even plant-specific level [22]. On the macro-level, it is found that, while price shocks immediately impact choice of fuel use in the short term, market-related answers to those imbalances both from the supply- and demand-side often compensate for them. This makes substantial fuel switching a long-term issue, connected to technology choice, investment decisions, lock-in effects and security of supply considerations [23]. This inertia and government policies may even delay or outweigh price signals, as Skea [24,25] points out in his analysis of the UK industry during the second half of the last century. This is underlined by process-specific investigations of

Akhtar et al. [26] on clinker burning and Hjermstad et al. [27] on coal-use infrastructure. Incremental changes however may be realized in the short-term in some industrial subsectors. Gessa-Perera et al. [28] assume a substitution ratio of petrol coke by waste tires in the production of clinker of 10% to be immediately implementable without major changes to the process.

While the infrastructure is of high relevance for any form of energy supply, grid-bound energy carriers like gas and electricity require special attention. Fuel switching to electricity in particular is tied to consideration of its generation, transmission and distribution. This includes high temporal and spatial resolution and is thus subject to specialized approaches. This thesis does not consider spatial or local aspects, but assumes values (electricity price, emission factor) to represent them. An estimate of renewable electricity generation is mentioned in chapter 4.

One of the main challenges to an adequate representation of the industrial energy demand in energy system models is the heterogeneity of the sector. Here, the manufacturing industry is investigated. This includes activities in which 'material is transformed into new products' [29]. On the European level, a similar allocation is used [30]. These classification systems identify between 13 and 24 main groups. In terms of energy demand, the most relevant branches within the sector can be identified as 'energy intensive', for example based on energy demand per unit of value added or per tonne of product [31]. For this thesis, the subsectors usually identified as energy intensive have been selected according to the Eurostat definition (Table 1.2).

Table 1.2: Industrial subsectors considered in this thesis [4,30]

Eurostat subsector	NACE Rev.2 classification	Energy intensive
Iron and steel	24.1, 24.2, 24.3, 24.51, 24.52	✓
Non-ferrous metals	24,4, 24.53, 24.54	✓
Paper and printing	17, 18	✓
Non-metallic mineral products	23	✓
Chemical industry	20	✓
Food, drink and tobacco	10, 11, 12	(✓)
Engineering and other metal	25, 26, 27, 28, 29, 30	✗
Other non-classified	13, 14, 15, 16, ...	✗
Refineries	19.2	✓

Despite this focus on the most energy intensive subsectors, there are still a multitude of products, technologies and processes involved. All of which induce different evaluation of attractiveness of the available technologies and energy carriers. Hence, data availability on a sufficient level of detail is acknowledged as one of the most important methodological issues for energy system models in all sectors and specifically industry [32–35]. A plausible representation of this heterogeneity includes not only a technological and economical but also a behavioural perspective [36].

Energy carrier choice is always connected to technology choice. This includes the immediate installation (e.g. furnaces, steam boiler), but also adjacent infrastructure (storage, grid access) and soft factors (qualified personnel, access to information). A prominent example of the relation of fuel mix and technology is the steel industry, whose carbon footprint (and its potential reduction) is often discussed related to the technology choice of blast furnace (BF) and electric arc furnace (EAF) e.g. by Arens et al. [15]. They conclude that, due to process restrictions present in the BF-route, new technologies must be applied to reduce the carbon-intensity of steel production. Hu and Zhang [37] identify the technological change towards EAF as the most effective way to reduce both energy consumption and emissions. However, they also find the potential limited due to domestic scrap availability, concluding that in the coming decades, steel demand will still outrun scrap availability in growing economies like China. This option therefore requires additional considerations about material availability and quality. There are investigations into short-term fuel switching in the steel industry though, mainly involving the use of biomass as reducing agent in the BF. Kumar et al. [38] discuss how macadamia shells could replace coke in blast furnaces, effectively reducing its dependency on coal. Additionally, technological requirements tied to the products and processes exist, for example, a required process temperature or chemical reactions taking place during the process. Considering long lifetimes of industrial installations, the technology stock is therefore important when the diffusion of energy carriers is modelled.

Traditionally, fuel switching is a domain of top-down econometric considerations. Its base assumption is that fuel in general can be used universally, with little or no explicit respect to distinct technological requirements. It proved difficult to be included in bottom-up models due to the fundamentally different nature of scope and methodology. Stern [11] provides an overview regarding econometric fuel switching studies, finding that 65% of these studies use a translog approach. Labandeira et al. [39] showed in a meta-analysis of price-elasticities of important energy carriers that the econometric top-down approach yields strongly diverging results, ranging from -2 to above 0[7]. On average however, they classify the investigated energy products as price inelastic. Major influences are the type of consumer (residential, industry, commercial) and the type of model and data used. They try to explain the deviations with factual reasons (country- and energy carrier-specific differences, sample period, economic crises) as well as methodological differences (used model, data, estimation method). Frondel [40] gives further insights in different interpretations of substitution elasticities. Another example of an econometric fuel switching investigation is Smyth et al. [41], who investigate fuel switching in the Chinese iron and steel sector using a log linear translog production and cost function (the same approach has also been applied by Lin [42]). They conclude that, while coal is a potential substitute of electricity, natural gas and oil, there are several restrictions to actual substitution of coal. Due to the nature of their approach, the four restrictions they mention (electricity generation type, high energy intensity, strategic policies, company-size) are policy-/ or economy-related, while technical requirements of the processes remain unmentioned. Thus, it remains unclear whether the theoretical exchangeability found can be applied. These results indicate that an approach on a higher level of detail is needed.

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7 Meaning that the investigated studies do not agree on the strength of a top-down effect of energy carrier prices on fuel switch, and some not even on the sign.

The econometric approach thus struggles to represent several of the aforementioned influences when explaining fuel switching by sector-wide sensitivities. Bottom-up models on the other hand represent individual technology groups of specific sectors. While they often lack the ability to consider cross-sector interactions, they are well suited to describe intra-sector developments on a detailed level, taking into account industry-specific properties, restrictions and opportunities.

The quantitative description of the effect of price changes on fuel choice and their implementation in a bottom-up energy system model is a major part of this thesis. Its main contribution to the methodology of energy system models is to show how a fuel switch model can integrate technology, economics and behaviour in a bottom-up approach. To support this effort, empirical data on behavioural preferences are gathered.

1.2 The implementation of fuel switch potentials

1.2.1 The theory of discrete choices

The use of random utility maximization (RUM) models originates in the 1970's effort to simulate consumer travel demand and modal choice as described by McFadden [43]. The models enhance the notion of strict economical decision-making (i.e. based only on the observed price) with individual preferences of the choosing subject. These preferences constitute a utility, which may vary among decision makers. The resulting utility values of each offered option, as well as the underlying preferences, are a priori unknown to the observer, yielding decisions that appear to be irrational or "random". McFadden [43] describes the random element as:

"[...] the randomness in utility could come from both inter-personal and intra-personal variation in preferences and from variations in the attributes of alternatives known to the decision-maker but not to the observer"

The core concept is the definition of 'utility' as the degree to which a given option (e.g. a mode of transportation or a brand of cereals) satisfies a persons' needs (e.g. mobility or a healthy breakfast). It is applied to organisations or companies accordingly in this thesis. Assuming rational decision-making, the option with the highest utility among all available options for a specific person is perceived as most attractive and will be picked. This utility can wary between persons and products. Utility cannot be measured directly for multiple reasons. For once, not all properties of all options or the decisions situation might be known, especially in the case of complex decisions. More importantly, however, the needs of the decision-making entity are generally hidden, to some degree even to itself. For modelling purposes, the utility is instead inferred, based on observed decisions or choice experiments, e.g. surveys. These observations or stated information can reveal decision patterns, which are called preferences. There are two ways to quantify these preferences: 'revealed preferences' are based on observations of real decisions while 'stated preferences' are based on simulated decision situations. Revealed preferences have the advantage that they describe real decisions that have actually led to actions. They do, however, offer limited variations and are of reduced value to describe the preferences for new options, e.g. new technologies or market models, for which a small number or no observed decisions exist. When they are derived from time series analysis, they may also show past preferences, rather than current ones. 'Stated preferences' on the other hand excel at the investigation of options not currently available on the market, as they allow creating virtual set of options or conditions. Due to this virtual decision environment, however, the yielded decisions can be subject to several biases. Foremost, the stated decisions do not have consequences for the decision maker, or those are limited. This could potentially underestimate barriers to technology diffusion.

The utility term is, in both cases, composed of a deterministic component and an unknown (stochastic) error term [44]. There are multiple options to solve the corresponding equation, each related to an assumption about the probability distribution of the error term. The most relevant are the probit and the logit model. The probit model assumes a normally distributed error term and yields a general applicability. However, it does not provide a closed form solution and is thus more complicated to apply and less transparent. The logit model on the other hand assumes the error term to be independent and identical distributed ('iid'-assumption). While this is most likely not the case for errors of real-world observations (the assumption of normal distribution is much more plausible), it simplifies the equation to a closed form (eq. 1) which can be interpreted and immediately shows properties beneficial for decision description: The choice probabilities π_k range between zero and one and their sum is one. The results obtained from iid-error terms and other assumptions like normal distribution are, according to Train [44], usually indistinguishable.

$$\pi_k = \frac{\exp(U_{i=k})}{\sum_i \exp(U_i)} \qquad \text{(eq. 1)}$$

However, other properties of this design require attention. Foremost, it requires careful selection of the available options. It can easily be shown that the number of options included in the set influences the outcome. This is caused by the 'independence of irrelevant alternatives' ('iia')-property of the logit model and is represented in the 'red bus/ blue bus' problem [44]:

"Consider the famous red bus/blue bus problem. A traveler has a choice of going to work by car or taking a blue bus. For simplicity assume that the representative utility of the two modes are the same, such that the choice probabilities are equal: $P_c = P_{bb} = 1/2$, where c is car and bb is blue bus. In this case, the ratio of probabilities is one: $P_c/P_{bb} = 1$.Now suppose that a red bus is introduced and that the traveler considers the red bus to be exactly like the blue bus. The probability that the traveler will take the red bus is therefore the same as for the blue bus, such that the ratio of their probabilities is one: $P_{rb}/P_{bb} = 1$.However, in the logit model the ratio P_c/P_{bb} is the same whether or not another alternative, in this case the red bus, exists. This ratio therefore remains at one. The only probabilities for which $P_c/P_{bb} = 1$ and $P_{rb}/P_{bb} = 1$ are $P_c = P_{bb} = P_{rb} = 1/3$, which are the probabilities that the logit model predicts."

This is, however, a counter-intuitive outcome. The availability of a differently coloured bus should not influence the attractiveness of the car. For model application, this iia-property means that the options offered to the model must be carefully selected to be sufficiently distinct. Else, their utility (and hence their market share) can be overestimated. For example, the Eurostat energy balances [4] consider four types of hard coal with slightly different properties. For a model of inter-coal substitution, these differentiations would be relevant, but when coal is competing against e.g. natural gas or biomass, these coal types should be aggregated to account for the iia-property.

McFadden [43] further shows that after the initial establishment of RUM in travel demand modelling, the concept of heterogeneity in preferences was spread to other fields, among them energy demand models. However, these applications were often restricted to the consumer-level, be it households, choice of car or telecommunication service provider. A notable application of a variant of RUM to industry, is the work of Rivers et al. [45]. They mention three dimensions of energy models of which two are relevant for this thesis: technology explicitness and behavioural realism. They make the point that, while bottom-up models generally excel in the former, they lack the latter due to concentration on techno-economic data. Another work in this regard is the application to fuel share calculation by Kesicki and Yanagisawa [32]. Their approach is based on top-down data of the world's energy demand in several important energy-intensive sectors (iron and steel, chemicals and petrochemicals, pulp and paper and cement). They derive the logit parameters by regression of historic fuel use data and conclude that better data on the behavioural aspects in the industrial sector as well as knowledge about the diffusion of energy saving technologies are needed. A recent example for a similar approach on this issue is how von Ruijven et al. [46] use the logit formulation in a nested variant to allocate energy carrier and technology choice directly by costs. They introduce technical limits to fuel use, e.g. a minimum share of electricity in EAF, which are exogenously described and amended by cost-efficiency calculations. Their model does not include a utility-formulation but relies on a minimal-cost approach, thus somewhat neglecting the influence of heterogeneity and behaviour differences on the decision outcome. They include a parameter similar to market homogeneity though, which yields a limited form of heterogeneity among sectors.

An alternative decision strategy includes the consideration of transaction costs, when they are high enough to affect the result. In this approach, satisficing or bounded rationality [14], not necessarily the objectively optimal solution is chosen but the next best solution satisfying the decision maker's needs. This decision strategy thus limits the ability of the decision maker to act according to his preferences. For this work, similar aspects are reflected in assumptions on market homogeneity.

1.2.2 The energy carrier choice in industry

Energy carrier choice in industry is subject to barriers and restrictions. An important technical restriction relevant for high-temperature processes is the heating value of the energy carrier. It describes the energy density and is closely related to the achievable flame temperature. Energy carriers with low heating value may not be able to reach required process temperatures or require preparation (drying and homogenization, fuel and air preheating). They may also require a higher amount of energy in total [47] than their high-caloric equivalents. Additionally, some processes use fuel not only as energy carrier but also as feedstock. In cement production, the raw meal binds mineral fuel ashes while forming clinker. Blast furnace operations use coke as reducing agent, to lower the smelting temperature and as mechanical support. Refineries inevitably generate and use fossil gases ('refinery gas') as fuel. Replacing them is, from both an economic and logistical perspective, currently unfeasible.

Additionally, the existing price structure supports the status quo of energy use. Foremost, fossil fuels often exclude or undervalue their GHG component. Including these costs in fossil fuel prices would mean to pay for any costs associated with their use. In the context of global warming, these costs are hard to calculate and subject to debate. The German Environmental Agency [48] estimated a value of 180€/tCO_2 in 2016. In the energy intensive industries however, which are subject to emission trading in the EU ETS, the current price for CO_2 ranges between 23 and 27€/t [49]. Fossil fuels are therefore subsidized, as their costs, measured in mitigation, adaptation and loss of wealth, are paid by future generations.

Another type of restriction is the inertia associated with technology stock. Even when fuel switching seems attractive, e.g. due to a price shift, it needs to be realized. As mentioned above, this includes technological change, often tied to investment cycles. In a simple approach, an equipment lifetime of 20 years means that a maximum of 5% of energy carrier use can change each year. However, as industrial processes comprise a variety of installations and infrastructure, which may have significant shorter or longer lifetimes. In reality, the actual age distribution of installations is thus of high importance to identify windows of opportunity in energy intensive industries. Joas et al. [50] estimate that until 2030, 53% of blast furnaces, 59% of steam crackers and 30% of cement kilns (by capacity) in Germany will require reinvestments until 2030. With their technical lifetime of 50-70 years, this reinvestment cycle may define the industrial structure of Germany and its climate impact for decades.

Considering these barriers, several approaches exist to facilitate fuel switching. The single most important driver is the economic incentive. Therefore, the energy carrier prices are the main factor. Some policies address these directly, e.g. taxes, the EU ETS and direct subsidies. Next to price-based policies, regulations can influence the (perceived) attractiveness of energy carriers. Examples include the EU Industrial Emissions Directive [51], which regulates local pollution from industrial installations and the limitation of the sulphur content of fuels to reduce the emissions of sulphur-dioxide. These and similar regulations induce efforts to use certain (mostly fossil) energy carrier. While it is not the purpose of these regulations to facilitate fuel switching, it may be a viable measure to comply with regulatory requirements[8]. Finally, the rate of stock exchange is an important descriptor. Shortened investment cycles may greatly increase the impact of economic incentives.

[8] At the same time, these regulations may limit the use of biomass in some applications.

1.3 Objective of the thesis

The description of energy system models helps to inform decision makers and develop appropriate policy instruments. Including fuel switch options is vital for model-based policy advice concerning energy system transformations. Understanding how the industries' heterogeneity, technical restrictions and economic factors interact is key to design a plausible of the potential for fuel switching. This representation must be detailed enough to allow for targeted policy design and robust enough to represent actual decision processes. Until now, this conflict has not been solved for the industry sector. The main challenges are the heterogeneity of the sector, the subsequent scarcity of detailed data on energy use, the neglected dimension of behavioural influences on energy carrier choice and consequently the lacking price-sensitivity of existing approaches.

Economic considerations of fuel switching are usually the core of energy system models for the industry sector, with the energy carrier price as the main determinant of its use (e.g. *PRIMES, NEMS*) [52,53]. Additional cost components like investments, maintenance and operations can also be considered. Technical restrictions, e.g. the need to switch burners when replacing coal with natural gas, are for example considered in the *SmInd*-model [54]. This requires a high level of detail and technical knowledge of the affected processes, and the approach to model the industry on a process-level is common by now [55]. All simulation (and some optimisation) approaches share the need to represent an imperfect market, in which the decisions are not always a direct result of price signals. This requirement often contradicts the techno-economic approach of bottom-up simulation: The objectively best option might not be the most successful, due to consumer preferences and barriers[9]. In the CIMS model for Canada [45], behavioural aspects are integrated in the competition between technologies, considering heterogeneous markets and consumer's implicit discount rates. However, empirical evidence on the parameters assumed for consumer behaviour is in general scarce or available on a strongly aggregated level. For Europe, no empiric evidence on behavioural aspects in industrial fuel switching on a level usable for bottom-up models is known so far.

This thesis therefore combines previous approaches to include economic, technologic and behavioural influences in an integrated approach to fuel switching in industry. It describes a model capable of simulating energy carrier choices in industry. It includes the heterogeneity of the sector in a bottom-up approach on a process level and utilizes this high level of detail to enhance existing statistics of energy use by additional dimensions that influence energy carrier choice. It generates insights in behavioural influences on energy carrier choice in industry. Finally, it applies the model to the case of German sectoral emission reduction targets of 2030. It addresses the following main research question:

[9] "*Consumers are not cost-minimizers*" [45]

"*How are fuel switch decisions made in the energy-intensive industry and how can they be integrated in a bottom-up energy system model to simulate energy carrier choice?*"

This main research question is divided into five sub-questions, each addressing an individual challenge. The sub-questions constitute the structure of the thesis.

1. What is the current use of energy in industrial processes in the EU28 and what is a meaningful differentiation of energy use for energy carrier choice? (Chapter 2)

2. Which fuel switch measures in important industrial processes in the EU ETS are discussed in literature and how do the existing potentials relate to emission reduction targets? (Chapter 3)

4. How do energy carrier preferences in industrial steam generation influence energy carrier choice and how can an energy system model include them? (Chapter 4)

3. How can a bottom-up energy system model describe fuel choices in energy-intensive industries and how can it be parametrized? (Chapter 5)

5. Which economic incentives are necessary to support fuel switching to achieve mid-term climate targets, considering economic, technical and behavioural influences? (Chapter 6)

According to the research questions, the thesis is divided into five chapters (Figure 1.5).

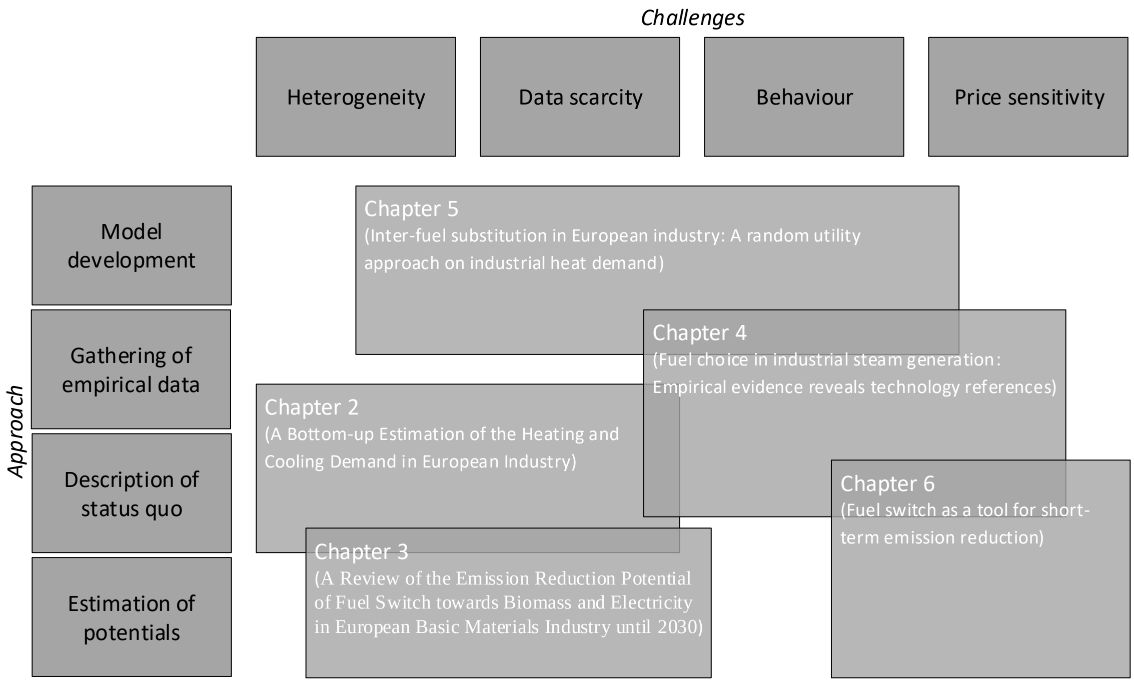

Figure 1.5: Approaches to address the challenges to fuel switch modelling in industry, by chapter

First, the data basis of energy use in industry is described and extended. Starting with energy balances, the additional dimensions of temperature level and application are introduced. They allow identifying important energy uses, appropriate technologies and potentials for fuel switching (chapter 2). Second, a literature review of fuel switch measures in important industrial processes is conducted. The identified measures are then synthesized into sector-specific potentials and compared to climate change mitigation targets (chapter 3). Third, the fuel switch model is developed and parametrized. A discrete choice approach is used to create a framework, in which preferences and economic influences govern energy carrier choice. Additionally, revealed preferences informing the model are derived from time-series analysis (chapter 4). Fourth, a survey is conducted among steam generating companies. The original data collected in this survey inform a technology stock model of steam generation and enhance expert-based parameters (chapter 5). Finally, chapter 6 operationalizes the previous chapters in an estimation of economic fuel switch potentials and the impact of price signals on their adoption. It estimates the contribution of fuel switching to German sectoral GHG mitigation targets (chapter 6).

1.4 Outline of the thesis

1.4.1 Chapter 2: Status quo of energy use

Energy balances are an important tool for researchers, because they serve as a point of reference for analyses of the future energy system. The effort needed to generate primary data (for example recurring surveys of energy users) limits these balances to aggregated levels. Usually, they provide information on a sectoral and sub-sectoral level for individual or groups of energy carriers. For bottom-up models, this aggregation is often not sufficient, as they may work on a higher level of detail. At the same time, compliance with established statistics is a major source of confidence for these models and a minimum requirement for relevant policy advice.

The energy balance provided by Eurostat can be seen as a reference for Europe, since it applies a harmonized framework to the data collected by the national statistical institutes of the member states. Several national institutions prepare end-use balances that include higher detailed data. However, these kind of balances are not available on a European level. In chapter 2, an approach is presented that disaggregates Eurostat's energy balances of the industry sector and adds the dimensions temperature level and end use (Figure 1.6). Based on the energy-demand model FORECAST, it maintains conformity with the EU energy balances but deepens the understanding of energy use. The novel approach of process-temperature-profiles (instead of subsector-profiles) allows explaining the heterogeneity among national economies and links the energy demand to verifiable data of the respective processes (activity, temperature and other characteristics).

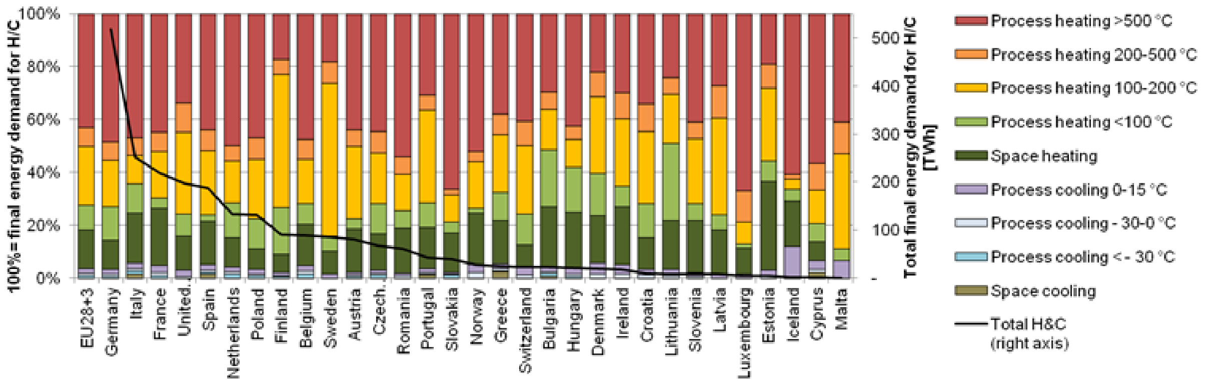

Figure 1.6: Industrial heating and cooling demand by temperature level and end use in the EU28 (+3)

1.4.2 Chapter 3: Theoretical fuel switch potentials

In 2015, industrial sector installations included in the European emission trading system (EU ETS) emitted 574 Mt CO_2-equivalent Greenhouse gas (GHG) emissions. Among them are production of clinker, lime and ammonia, iron, mineral oil products and others. The emission intensity of these installations is closely tied to the fuel type used and fuel switching is potentially an important GHG-reduction measure. However, the technologies used pose challenges to fuel switching and thus, potentials cannot be investigated on an aggregated level. In chapter 3, the technical potential to use biomass and electricity with existing or available technologies in important industrial processes is reviewed. The review is restricted to technologies with a technology readiness level (TRL) of 6 or higher. This limitation allows the potentials to become relevant until 2030. The investigated industries account for 95% of the total verified emissions in the EU ETS industrial sector 2015 and 64% of total industrial emissions of the EU28.

1.4.3 Chapter 4: Behavioural influences

Scenario analysis of the energy system relies largely on model calculation and techno-economic data. Companies are assumed to show a more rational decision behaviour than, for example, households. In the industrial context, energy system models largely neglect the influence of behavioural aspects or try to quantify qualitative expert-judgment. At the same time, pure techno-economic models fail to reproduce energy use patterns, often overestimating the appeal of low-emission technologies.

Empirical evidence on technology preferences in industry is scarce. In chapter 4, original survey results for preferences in industrial steam generation technologies in Germany are presented. The acquired data are a novelty for the industrial sector in a European country. They are obtained by a survey among industrial steam users in which the attractiveness of different systems is measured in a discrete-choice experiment. The generated data is used to inform the price-sensitivity of a fuel stock model of steam generation [56].

1.4.4 Chapter 5: Model design and construction

Top-down models often struggle to include heterogeneous structures due to their lack of technological explicitness. This impairs their usability in terms of policy design. On the other hand, bottom-up models assume a techno-economic point of view, underestimating transaction costs, system-wide feedbacks and hidden costs or risk-related premiums to technology adoption [14]. Behavioural aspects of investment decisions are often neglected. Thus, these approaches create a range of interpretations with different conclusions on economic and technical viability. Models trying to combine the approaches by including behavioural aspects in techno-economic models are called hybrid models [36].

This paper adds behavioural aspects with a discrete choice to a bottom-up model describing industrial high temperature energy demand. It enhances techno-economic considerations by modifying cost estimates of energy supply options with empirical data on energy use. In addition to model construction and description, a parameter set is presented. This parameter set is differentiated by country and subsector. It informs the model of the preferences for each available energy carrier. The model's parameters are estimated based on observed fuel choices between 1992 and 2013. The resulting revealed preferences are used to inform the model on fuel switching in industrial furnaces.

1.4.5 Chapter 6: Fuel switch simulation

While potentials for sustainable energy use in industrial processes exist, they are often not economically feasible. Fossil fuels benefit from the externalization of important cost components, especially those related to GHG emissions. To facilitate fuel switching, the economic properties of alternative energy supply must be considered. In the previous chapters, challenges to increase the economic responsiveness of fuel switch models have been described. The fuel switch model developed in chapter 5 explains fuel switching with price signals technical properties and behavioural influences.

Chapter 6 applies this fuel switch model and makes use of the empirical data gathered on energy carrier choice in steam generation (chapter 5) and high temperature applications (chapter 3). To investigate the economic conditions necessary to realize the potentials described in chapter 2, sensitivity analysis of the model until 2030 are performed. These novel analyses with highly endogenous decision modelling highlight windows of opportunity and the most influential measures to reach 2030 climate targets.

Chapter 7 summarizes the findings of the previous chapters, discusses limitations of the modelling approach and puts them in a broader perspective. Additionally, further research, in particular on the gap between 2030 and GHG neutrality until 2050 is discussed.

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2 A Bottom-up Estimation of the Heating and Cooling Demand in European Industry[10]

Abstract

Energy balances are usually aggregated at the level of subsector and energy carrier. While heating and cooling accounts for half the energy demand of the European Union's 28 member states plus Norway, Switzerland, Iceland (EU28+3), currently, there are no end use balances that match Eurostat's energy balance for the industrial sector. Here, we present a methodology to disaggregate Eurostat's energy balance for the industrial sector. Doing so, we add the dimensions of temperature level and end use. The results show that, although a similar distribution of energy use by temperature level can be observed, there are considerable differences among individual countries. These differences are mainly caused by the countries' heterogeneous economic structures, highlighting that approaches on a process level yield more differentiated results than those based on subsectors only.

We calculate the final heating demand of the EU28+3 for industrial processes in 2012 to be 1035 TWh, 706 TWh and 228 TWh at the respective temperature levels >500°C (e.g. iron and steel production), 100-500°C (e.g. steam use in chemical industry) and <100°C (e.g. food industry); 346 TWh is needed for space heating. In addition, 86 TWh is calculated for the industrial process cooling demand for electricity in EU28+3. We estimate additional 12 TWh of electricity demand for industrial space cooling.

The results presented here have contributed to policy discussions in the EU (European Commission 2016), and we expect the additional level of detail to be relevant when designing policies regarding fuel dependency, fuel switching and specific technologies (e.g. low-temperature heat applications).

10 This chapter has been published in Energy Efficiency as *Rehfeldt, M.; Fleiter, T.; Toro, F. (2017): A Bottom-up Estimation of the Heating and Cooling Demand in European Industry.*

2.1 Introduction and Motivation

Energy balances are an important tool for researchers and policy makers alike, because they serve as a point of reference for analyses of the future energy system. However, the effort needed to generate primary data (for example recurring surveys of energy users) limits these balances to aggregated levels. Usually, they provide information on a sectoral and subsectoral level for individual or groups of energy carriers. The energy balance provided by Eurostat can be seen as a reference for Europe, since it applies a harmonized framework to the data collected by the national statistical institutes of the member states. While virtually all member states of the EU generate national energy balances, the availability of end-use balances is limited[11], especially in the industry sector. Currently, Eurostat does not provide end-use energy balances. The difficulties concerning the compatibility of national energy balances are described, for example, in the quality report of the European Union on energy statistics (European Commission 2014). EU regulation No. 1099/2008 and its amendments demand a "greater focus (...) on final energy consumption" and more detailed and comparable energy statistics (European Parliament 2008). Thus, while not explicitly defining end-use dimensions, there is a clear need for data beyond the conventional dimensions of subsector and energy carrier. Additionally, more detailed energy balances could help to identify relevant applications for energy efficiency research by enabling more technology-focused approaches.

Strong heterogeneity among the countries of the EU28 + Norway, Switzerland, Iceland (EU28+3) can already be observed at subsector level (Figure 2.1), as it is also supplied in the Eurostat energy balances (Eurostat 2016-2)[12]. In terms of energy use, the most important sectors are iron and steel (22%, 533 TWh), chemical and petrochemical (19%, 448 TWh) and non-metallic minerals (15%, 353 TWh). The end-uses of this energy, and in particular the temperature levels of process heat, are not investigated in these energy balances. With the results of this paper, the heterogeneity highlighted here is explained on a more disaggregated level based on our bottom-up approach.

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11 In the EU project *"Mapping and analyses of the current and future (2020-2030) heating/ cooling fuel deployment (fossil/ renewables)" (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016)*, a comprehensive analysis has been carried out of the availability of end-use balances in the EU28 +3, including the residential and tertiary sector as well.

12 The illustration shows model results for heating and cooling demand presented at the aggregation level also available in energy balances. The actual energy balances include additional electricity for non-heating/cooling uses.

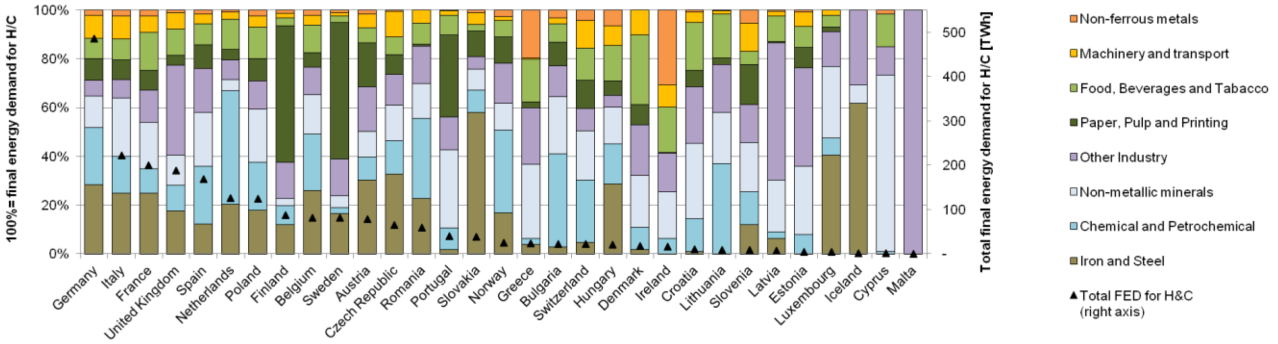

Figure 2.1: Final energy demand for industrial heating and cooling by country and subsector in EU28+3 in 2012 (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016)

End-use balances break down the final energy demand into specified use categories as space and process heating/cooling, sanitary hot water and electrical appliances such as motors and lighting. For industry, only Germany, Switzerland, the United Kingdom and Austria provide more or less complete end-use balances with only Switzerland presenting data on all the investigated categories (space heating, hot water, appliances, process heating and cooling) (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016).

This lack of end-use balances in the EU is not only related to the general challenge of collecting detailed data on energy demand, but can be attributed in particular to industry-specific issues: Evaluating process heat demand requires detailed knowledge about the characteristics of the various processes applied in European industry, and allocating temperature levels requires even more detailed information. And while individual processes, especially those with high overall or specific energy demand (energy-intensive industries), are well researched in terms of energy efficiency, the availability, comparability and reliability of the related data are an issue. Energy demand simulation models can be used to fill existing data gaps when complete data sets are required. The above mentioned issues, however, mean that top-down approaches lack the desired level of detail to reflect industry's heterogeneity, while bottom-up approaches struggle with the availability of detailed technological and economic input data. Furthermore, some important aspects of industrial production like internal heat use and process integration cannot be represented at subsector level.

Previous work on this topic includes Pardo et al. (2013), who used similar approaches to the questions of how to assign a share of final energy for heating, or how to define temperature levels for industrial fuel use. They did so, however, with an emphasis on energy transformation from primary to useful energy for the industrial, residential and tertiary sector in the EU27. They present Sankey diagrams with the dimensions of subsector and temperature, stating distinct temperature profiles per subsector. Their results show that natural gas, petroleum products and coal products cover 83% of primary energy consumption. They supplement this result, which is in line with statistical data, by splitting the industrial useful energy demand into three temperature levels and the respective shares of useful energy in the EU27 (low 22%, medium 20%, high 58%). However, the absolute values provided are not directly comparable with Eurostat's energy balance, as they focus on useful energy.

Naegler et al. (2015) present two different approaches to disaggregating the final industrial energy demand of the EU28 for the year 2012, and conclude that an improved data basis is needed to achieve robust results. They calculate between 8150 and 8518 PJ industrial heat demand for the EU 28, differentiated by five end-uses (space heating and hot water, four process heat temperature levels) and country. However, due to limited access to national bottom-up data, they applied Germany's end-use structure, as this was available in its national end-use balance. They assume that processes are the same across countries. They show that many approaches to the disaggregation of energy demand in the EU28 rely on similar data sets (e.g. subsector distribution of energy demand), thus producing similar results. This implies that different approaches are needed to substantiate or challenge the robustness of the available studies.

Both Pardo et al. (2013) and Naegler et al. (2015) assign a share of final energy to heating and cooling purposes and temperature levels, assuming similar shares across countries. However, both allocate this information at the level of subsectors and cannot account for substantial structural differences across countries within subsectors. For example, the iron and steel sectors in Italy and Germany feature significantly different shares of electric and oxygen steel.

We want to contribute to this line of research by introducing an approach that includes differences in national economic structures by incorporating process-specific information. This allows us to create technology-based temperature profiles for individual processes, which results in different temperature profiles for industrial subsectors in different countries due to their different economic structure. Thus, we reduce the dependency on national end-use balances that neglect country-specific differences when applied to the entire EU28+3.

In this paper, we present a methodology to disaggregate energy balances into end-use balances, with the focus on industrial heating and cooling demand by applying the bottom-up energy demand model FORECAST. We show how gaps in data availability are closed and the bottom-up model results are connected to Eurostat's energy balance (Eurostat 2016-2), enhancing it with the dimensions of end-use and temperature level.

In "Methodology and Data", we present a description of the model and important data assumptions. In "Results", we present selected dimensions of the model results, namely temperature distribution and energy carrier use, which are discussed in the last section. There, we also introduce the concept of "bottom-up" coverage as a quality criterion. We conclude with our thoughts on how to proceed with the methodology, and improve the results.

The results presented here were generated in a project for the European Commission and the full report and data sets (including non-heating/ cooling use which is not presented here) are available online (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016).

2.2 Methodology and Data

The model FORECAST-Industry (Fraunhofer ISI, IREES, TEP 2017) works on the level of industrial processes, which are grouped into industrial subsectors and whose production figures vary among countries. The definitions of industrial subsectors and energy carriers are based on the energy balance of Eurostat. The model is divided into three parts, which are described following its workflow: Industrial processes (including process heat and cold), space heating/ cooling and bottom-up/top-down matching (Figure 2.2). Processes and space heating/ cooling are calculated using a bottom-up approach (top left/ right), each based on an activity value and specific energy demand. The resulting bottom-up value is matched (bottom right) to top-down statistical values (e.g. Eurostat energy balance).

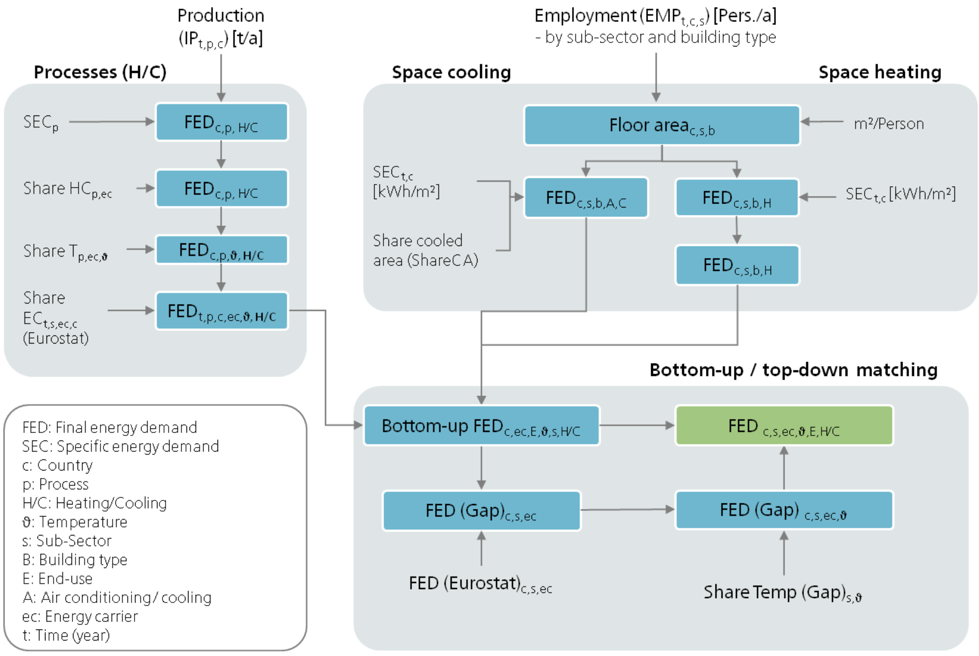

Figure 2.2: Schematic representation of the end-use balance model calculation for the industry-sector (FORECAST-Industry)

Processes

The heating and cooling energy demand of about 60 of the most energy-intensive industrial processes is calculated using a bottom-up approach as shown in equation (1) (see also Figure 2.2). The considered dimensions are:

- Countries *c* (European Union member states plus Switzerland, Iceland, Norway (EU28+3)
- Industrial subsectors *s* (iron and steel, chemical industry, non-metallic mineral products, paper and printing, non-ferrous metals, food, drink and tobacco), each with several industrial processes *p* assigned to them

- Energy carriers *ec* based on the energy balance of Eurostat (2016-2). Some are grouped (ambient heat, solar energy, waste non-RES, district heating, biomass, coal, geothermal, waste RES, electricity, fuel oil, other fossil, natural gas). Note that the actual energy carrier share per country and subsector is taken from Eurostat (2016-2) and not calculated bottom-up
- Temperature level θ (<100°C, 100°C-200°C, 200°C-500°C, >500°C)

$$FED_{p,c,ec,\vartheta} = IP_{p,c} * SEC_p * ShareEC_{s,ec,c} * ShareH/C_{p,ec} * ShareT_{p,ec,\vartheta} \quad (1)$$[13]

With *FED* as the final energy demand of a process, *IP* as its activity (production), *SEC* as the specific energy demand, *ShareEC* as the energy carrier share (taken at subsector level from the Eurostat energy balance), *ShareH/C* as the share of heating and cooling demand in the total energy demand and *ShareT* as the distribution of the processes' energy demand among the different temperature levels.

The industrial production per process and country *IP* in tonnes is based on several sources, of which some important ones are given in Table 2.3. A more complete picture of the sources used is given in (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016). The actual values per process (sum of EU28+3) are given in Table 2.1.

The specific energy consumption (*SEC*) is based on a variety of sources and process descriptions which are, due to the importance of this value, presented explicitly for each process in Table 2.1. The values give the total energy demand per tonne of product. They are not country-specific, as the analysed sources do not allow this differentiation. Instead, we have to assume that this basic process property does not vary significantly among the investigated countries. We call this assumption *process equals process*. Note that this is merely a simplification due to data availability for the purpose of the model. This constraint applies to all the technology data given in Table 2.1.

The energy carrier share in the respective subsectors *ShareEC* is not based on a bottom-up calculation but taken from the energy balances (Eurostat 2016-2) as an average per subsector (each process uses the energy carrier distribution of its subsector). Thus, although it is country-specific, the energy carrier distribution cannot be investigated at process level.

The share of heating and cooling in total energy demand *ShareH/C* is based on the same sources as the specific energy consumption. It is mainly relevant for the share of electricity used in cooling (e.g. 96% of the electricity used in the oxygen production process is used for cooling), as fuels are

13 The analysis presented here only comprises one base year, so there is no temporal dimension included. When used in scenario analysis, both the industrial production ($IP_{p,c}$) and the energy carrier shares ($ShareEC_{s,ec,c}$) may change each year.

considered to be used for heating purposes only (this may change if sorption cooling becomes more important).

The temperature profile *ShareT* of the processes is likewise based on the process descriptions given in Table 2.1 and shows which part of the total heating demand in a process is needed at which temperature level (e.g. 67% of the energy demand of blast furnaces is required above 1000°C). To overcome the weakness of subsector-level temperature shares, we allocate the temperature shares and energy demand on the level of about 60 individual energy-intensive processes. This allows us to approach the processes using a technology-based methodology, which derives the required data from process descriptions based on the products produced and the technologies applied. The constraints of the *process equals process* concept apply.

Based on extensive literature analysis, we compile temperature profile and specific energy demand values (Table 2.1) of industrial processes. These process-specific data (SEC, temperature profile) aim to take the technical properties of the processes into account. These include economic considerations (i.e. which technology is applied the most) and auxiliary technologies (e.g. waste heat recovery, flue gas treatment). Analogies between individual process steps (e.g. common temperature profile elements when controlled cooling takes place (glass, ceramics) or when the product group inherently disallows very high temperatures (e.g. food products)) are used where possible and needed. The most important indicator is the highest temperature of the process, i.e. which temperature has to be achieved to create the final product. Medium temperature ranges often occur in rather opaque process descriptions (e.g. glass slowly cooled to room temperature[14]). The majority of process descriptions were found in subsector-specific standard literature (Blüchel et al. 1999; Weissermel, Arpe 1998; Winnacker-Küchler 2006), others in previous attempts to assemble consistent process profiles (Fleiter et al. 2013), scientific articles on established and new process technologies (e.g. Arens et al. 2012; Arens et al. 2016; Hara et al. 1999; Cheeley 1999) and information material from companies where other sources were scarce (e.g. on direct and smelting reduction (Midrex 2013; Primetals 2015)).

14 It may be unclear, for example, whether this cooling is carried out actively (with additional energy demand or waste heat use) or passively.

Table 2.1: Investigated industrial processes, their specific energy consumption (SEC), process heating temperature distribution and the share of total electricity demand used for process heat

Subsector	Process	Energy demand: Fuels (GJ/t)	Energy demand: Electricity (GJ/t)	Share of electricity demand used for process heat (1)	Activity 2012 EU28+NO,IS,CH (Mt)	Temperature distribution (1): <100°C	100°C - 200°C	200°C - 500°C	500°C - 1000°C	>1000°C	Based on
Iron and steel	**Sinter**	2.24	0.13	0.00	117.63	-	-	0.20	0.80	-	Arens et al. 2012, Arens et al. 2016
	Blast furnace	11.64	0.60	0.00	107.85	0.01	0.01	0.11	0.20	0.67	Arens et al. 2012, Arens et al. 2016
	Electric arc furnace	0.98	2.28	0.95	98.76	-	0.01	-	0.10	0.89	Arens et al. 2012, Arens et al. 2016
	Rolled steel	2.39	0.60	0.10	183.51	-	-	-	0.20	0.80	Arens et al. 2012, Arens et al. 2016
	Coke oven	3.20	0.12	0.00	46.33	-	-	-	0.20	0.80	Brauer 1996
	Smelting reduction	15.00	0.42	0.00	0.00	-	-	-	0.20	0.80	Hara et al. 1999, Primetals 2015
	Direct reduction	15.00	0.42	0.00	0.66	-	-	0.20	0.80	-	Midrex 2013, Cheeley 1999
Non-ferrous metals	**Aluminium, primary**	5.20	53.64	0.05	4.02	-	-	-	1.00	-	Fleiter et al. 2013, Winnacker-Küchler 2006
	Aluminium, secondary	9.00	1.67	0.30	3.27	0.28	-	0.30	0.42	-	Krone 2000
	Aluminium extruding	4.20	4.80	0.30	2.18	-	-	1.00	-	-	Krone 2000
	Aluminium foundries	7.20	5.60	0.30	2.43	-	-	-	1.00	-	Fleiter et al. 2013, Krone 2000
	Aluminium rolling	3.30	2.20	0.30	3.58	-	-	1.00	-	-	Krone 2000
	Copper, primary	8.00	2.79	0.20	2.08	-	-	-	-	1.00	Fleiter et al. 2013, Winnacker-Küchler 2006
	Copper, secondary	4.00	2.33	0.10	0.85	-	-	-	1.00	-	Winnacker-Küchler 2006
	Copper further treatment	2.00	3.78	0.15	5.20	-	-	1.00	-	-	Winnacker-Küchler 2006
	Zinc, primary	1.00	15.90	0.01	2.68	-	-	-	-	1.00	Winnacker-Küchler 2006
	Zinc, secondary	1.00	0.60	0.01	0.09	-	-	1.00	-	-	Winnacker-Küchler 2006
Pulp and paper	**Paper**	5.50	1.91	0.01	100.46	0.05	0.88	0.05	0.02	-	Fleiter et al. 2013, Fleiter et al. 2012,van Deventer 1997
	Chemical pulp	12.65	2.30	0.01	26.91	-	1.00	-	-	-	Fleiter et al. 2013, Fleiter et al. 2012, Bakhtiari et al. 2010
	Mechanical pulp	-2.01	7.92	0.01	9.85	1.00	-	-	-	-	Fleiter et al. 2013, Fleiter et al. 2012, Laurijssen et al. 2012
	Recovered fibres	0.54	0.94	0.01	51.81	-	1.00	-	-	-	Fleiter et al. 2013, Fleiter et al. 2012, Laurijssen et al. 2012
Non-metallic minerals	**Container glass**	5.78	1.41	0.04	22.45	0.02	0.19	0.19	0.30	0.30	BREF Glass 2013, Büchel et al. 1999
	Flat glass	10.92	3.32	0.00	14.36	0.02	0.21	0.43	0.12	0.22	BREF Glass 2013, Büchel et al. 1999
	Fibre glass	4.92	1.81	0.20	2.70	0.02	0.19	0.19	0.30	0.30	BREF Glass 2013, Büchel et al. 1999
	Other glass	11.48	5.05	0.17	2.02	0.02	0.22	0.22	0.22	0.32	BREF Glass 2013, Büchel et al. 1999
	Houseware, sanitary ware	24.24	4.82	0.01	0.57	0.30	-	-	0.05	0.65	BREF Ceramic 2007, Büchel et al. 1999, Fleiter et al. 2013
	Technical, other ceramics	12.11	3.23	0.01	0.68	0.30	0.15	0.15	0.25	0.15	BREF Ceramic 2007, Büchel et al. 1999, Fleiter et al. 2013
	Tiles, plates, refractories	5.46	0.88	0.01	4.66	0.07	0.11	0.07	0.18	0.57	BREF Ceramic 2007, Büchel et al. 1999, Fleiter et al. 2013
	Clinker calcination-dry	3.50	0.14	0.00	172.06	-	-	0.10	0.60	0.30	Rahman et al. 2013, Patil&Khond 2014, Büchel et al. 1999
	Clinker calcination-semidry	4.00	0.16	0.00	10.34	-	-	0.10	0.60	0.30	Rahman et al. 2013, Patil&Khond 2014, Büchel et al. 1999
	Clinker calcination-wet	5.50	0.16	0.00	5.71	-	-	0.10	0.60	0.30	Rahman et al. 2013, Patil&Khond 2014, Büchel et al. 1999
	Gypsum	1.00	0.20	0.00	201.86	-	0.50	0.30	0.20	-	Bundesverband der Gipsindustrie 2013, Büchel et al. 1999
	Bricks	1.40	0.20	0.00	89.26	0.20	-	-	0.60	0.20	Fleiter et al. 2013, Dondi et al. 1997
	Lime burning	3.70	0.14	0.00	40.00	-	-	-	0.40	0.60	Gutierrez, Vandecasteele 2011, Büchel et al. 1999
Basic chemicals	**Adipic acid**	26.91	1.44	0.00	0.59	-	0.50	0.25	0.25	-	Fleiter et al. 2013, Weissermel, Arpe 1998
	Ammonia (synthesis gas)	11.27	0.48	0.00	18.00	-	-	-	0.66	0.33	Fleiter et al. 2013, Büchel et al. 1999
	Calcium carbide	6.12	8.32	0.95	0.34	-	-	-	-	1.00	Fleiter et al. 2013, Weissermel, Arpe 1998
	Carbon black	64.75	1.78	0.00	1.59	-	-	-	-	1.00	Fleiter et al. 2013, Büchel et al. 1999
	Chlorine, diaphragm	0.00	10.69	0.00	1.71	-	-	-	-	-	Fleiter et al. 2013, Büchel et al. 1999
	Chlorine, membrane	1.85	10.04	0.00	6.86	-	1.00	-	-	-	Fleiter et al. 2013, Büchel et al. 1999
	Chlorine, mercury	0.00	12.82	0.00	3.91	-	-	-	-	-	Fleiter et al. 2013, Büchel et al. 1999
	Ethylene	35.90	0.00	0.00	14.05	-	-	-	1.00	-	Fleiter et al. 2013, Weissermel, Arpe 1998
	Methanol (synthesis gas)	15.03	0.49	0.00	2.14	-	-	-	0.22	0.78	Fleiter et al. 2013, Weissermel, Arpe 1998
	Poly arbonate	12.86	2.66	0.00	0.85	-	1.00	-	-	-	Fleiter et al. 2013
	Polyethylene	0.64	2.04	0.00	8.94	-	1.00	-	-	-	Fleiter et al. 2013
	Polypropylene	0.79	1.15	0.00	8.64	-	1.00	-	-	-	Fleiter et al. 2013
	Polysulfones	24.49	3.06	0.00	0.36	-	1.00	-	-	-	Fleiter et al. 2013
	Soda ash	11.33	0.33	0.00	9.82	0.30	0.40	-	-	0.30	Fleiter et al. 2013, Büchel et al. 1999
	TDI	26.69	2.76	0.05	0.60	-	1.00	-	-	-	Weissermel, Arpe 1998
	Titanium dioxide	34.23	3.34	0.00	0.45	-	0.30	0.23	0.35	0.12	Fleiter et al. 2013, Büchel et al. 1999
Food, beverages and tobacco	**Sugar**	4.50	0.71	0.00	17.69	0.10	0.60	-	0.30	-	Fleiter et al. 2013, Lauterbach et al. 2012
	Dairy	1.57	0.53	0.05	69.64	0.90	0.10	-	-	-	Fleiter et al. 2013, Lauterbach et al. 2012
	Brewing	0.97	0.39	0.05	39.36	0.55	0.45	-	-	-	Fleiter et al. 2013, Lauterbach et al. 2012
	Meat processing	2.04	1.55	0.05	58.48	0.40	0.60	-	-	-	Fleiter et al. 2013, Lauterbach et al. 2012
	Bread & bakery	2.40	1.45	0.45	24.65	0.20	0.33	0.47	-	-	Fleiter et al. 2013, Lauterbach et al. 2012

Sometimes the most relevant heat demand occurs not in the main production process but in necessary or beneficial side processes (e.g. drying residues in sugar production, preparing lye for chlorine production in the membrane process, producing synthesis gas in several chemical processes). In these cases, the process definition needs to be extended (e.g. as noted in Table 2.1, ammonia and methanol production includes synthesis gas as a process step). In general, processes and products with high macroeconomic relevance are documented the most thoroughly (e.g. steel, cement, bulk chemicals), while smaller product groups (e.g. special ceramics) are harder to capture due to their heterogeneity. Processes with relatively low energy intensity (e.g. food) are also less well documented, probably because the manufacturer's focus here is not on energy. Sources for these processes are instead often characterised by a technology-centred approach (e.g. supply of low-temperature process heat via solar thermal systems (Lauterbach et al. 2012)).

As some of the sources used are quite old, it may be argued that the values are outdated. And while we constantly update the process database where possible, we address this argument with several measures and assumptions because new data cannot be generated at will:

- The most energy intensive processes usually experience evolutionary efficiency improvements (in contrast to revolutionary). One part of FORECAST simulates these incremental energy savings. It is not presented here but the included efficiency measures are discussed in Fleiter at al. (2013).
- We assume that the temperature distribution of processes does not change significantly over time.
- The values presented here do not reflect the best available technology (BAT) but try to capture the actual average stock, which is slower to change.
- Finally, as the actual SEC does vary from the values presented in Table 2.1, we emphasize the concept of *bottom-up coverage* (see below) as a quality criterion. If energy efficiency increases, this value will change and indicate sectors that need updated data.

Thus, while we are constantly searching for up-to-date data, the model does show some resilience regarding outdated specific energy consumption data.

Our definition of the temperature levels used is given in Table 2.2.Space heating is assumed to be supplied below 100°C.

Table 2.2: Definition of temperature levels for industrial process cooling and process heating

End-use	Temperature level	Comment
Process cooling	<-30°C	Mostly air separation in chemical industry
	-30-0°C	Mostly refirgeration in food industry
	0-15°C	Mostly cooling in food industry
Process heating	<100°C	Low temperature heat (hot water) used in food industry and others
	100-200°C	Steam, mostly used in paper, food and chemical industry
	200-500°C	Steam, mostly used in chemical industry
	>500°C	Industrial furnaces in steel, cement, glass and other industries

Table 2.3: Sources of industrial production figures

Subsector/ process	Data source
Iron and steel	World Steel Association 2014
Cement	Cembureau 2013
Glass	Glassglobal 2017
Pulp and paper	German Pulp and Paper Association (VDP) 2016, UNdata 2017 (FAO)
Aluminium and copper	US Geological Survey 2017
Chemicals: Ammonia	UNFCC 2017
Chemicals: Ethylene	UNFCC 2017
Chemicals: Oxygen	Eurostat
Chemicals: Methanol	UNFCC 2017
Chemicals: Chlorine	Eurochlor 2017
Food, drink and tobacco	UNdata 2017 (FAO)

In order to include temperature levels, we assume that all fuels are used to produce heat, stated in *ShareH/C*[15] in (1), while the major part of electricity (estimated to be around 90%) is used in non-heat applications. Exceptions to this are electric arc furnaces in steel and calcium carbide production and some electric melting furnaces. We assume that other applications for fuel use (like direct mechanical energy) are negligible. On-site generation of electricity is considered part of the transformation sector in line with the Eurostat energy balance's definition. However, the model does include the heat produced in small combined heat and power installations.

Non-heat energy use (e.g. in cross-cutting technologies such as motor appliances or lighting) is tracked to complete the energy balance, but not presented here. This non-heat energy use consists solely of electricity (see definition of *ShareH/C*).

Process cooling

Process cooling is used in industry for different purposes. In Europe today, the majority (over 90%) of refrigeration systems in industry are based on compression technology powered by electricity. Only stationary cooling units are analysed; mobile cooling applications are not included. It is assumed that production processes in the individual European countries do not differ significantly in their characteristic properties for the production of process cold; *process equals process* (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016).

In contrast to the process heating side, there is hardly any statistical information available on process cooling generation in Europe. Scientific studies are also rarely available (European Commission 2007; European Commission 2011; SVK 2012; VDMA 2011; UBA 2015). There are large data gaps for process cooling applications (number of units, capacity of refrigerating plants, energy efficiency, information about maintenance and service, etc.) in the various European countries. Technology stock data is rather limited and is partially found in EcoDesign preparatory studies (European Commission 2007; European Commission 2011). The stock of refrigeration systems remains not at a constant level

15 The share of energy demand used for heating and cooling (ShareH/C) translates the total energy demand given by the SEC into process heat demand.

over the years. Its development depends on the assumed cooling demand and the lifetime of existing and new systems. After reaching the maximum lifespan, existing refrigeration systems leave the stock. New refrigeration systems are added as required. In industry, the assumed lifetime for calculations is 20 years; however, the lifetime of these systems depends also on the size of the installed devices (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016). In the services sector, the average lifetime was estimated to be 15 years. Other estimates of typical lifetime spans of domestic refrigeration systems are 12- 20 years, of transport refrigeration systems 6 – 10 years and of chillers 15-30 years. The real lifetime of refrigeration systems depends on various influencing factors, not only the size of the system. Therefore, data on lifetime of refrigeration systems should only be taken as estimates.

Process cooling data are not recorded anywhere and the area of process cooling is not represented in Eurostat statistics. This is why the relevant associations in Europe and at member state level as well as cooling experts in some countries (Germany, Switzerland, United Kingdom, Austria, and Belgium) were contacted directly with the objective of collecting public and non-publicly available data. A formal data request including a template of the desired information was sent to over 25 different institutions in Europe (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016). The response rate was reasonable (over 50%), but the requested data was non-existent in almost all cases.

Furthermore, there are very individual cooling process solutions for different types of clients and aggregated information has not been collected, except in some member states where studies have been conducted at sector level on energy use and the demand for process and space cooling (e.g. Switzerland). We undertook in-depth desk research and analysis of specific cooling studies in Germany, Switzerland and the United Kingdom. On several occasions, the authors of these studies (cooling experts) were contacted directly as were the producers of particular chemicals (gases) with an especially high demand for cooling.

Based on the high complexity and the lack of resilient data concerning process cooling in European industry, it was necessary to make expert-based technical assumptions (stock of refrigeration plants, average capacity size for cooling systems (per branch), typical full load hours per branch, specific energy demand for process cooling per energy-intensive industrial process, allocated energy for process cooling, analysis per branch, etc.). For example, different full load hours of cooling devices were assumed depending on the average temperature in the various countries. In order to validate the assumptions for the calculation of the technology stock (e.g. full load hours, average installed capacity), interviews were conducted with organizations and experts. These assumptions were included when calculating the energy demand for process cooling in European industry. Therefore, the results contain uncertainties that are estimated to amount to ±25%.The indication of such a range was discussed with cooling experts. All experts considered such an indication to be useful in order to accommodate the uncertainties in the cooling market and the cooling applications.

Space heating/ cooling

Similar to the calculation of process energy demand, but on a subsectoral level, the final energy demand for space heating and cooling in industry (FED) results from the activity, employees (EMP) (Eurostat 2016-1), and specific energy demand per square metre of floor area (SEC). The latter is adjusted to countries using the European heating/cooling index EHI/ECI described by Werner (2006, 2015), (*EH(C)I*). He states that the specific energy demand is proportional to the square root of the heating/cooling degree-days, rather than directly proportional. Table 2.4 and Table 2.5 show representative values of floor area per employee (EMPArea) and SEC. The final energy demand is calculated individually for heating and cooling but shares the data input of heated/cooled area (*EMP*, *EMPArea*).

Table 2.4: Area per employee in m² by industrial subsector and building type (assumptions based on Biere (2014))

m²/Employee	Building Type	
Subsector	**Production**	**Office**
Iron and steel	82	67
Non-ferrous metals	82	68
Paper and printing	82	123
Non-metallic mineral products	82	124
Chemical industry	82	112
Food, drink and tobacco	82	174
Engineering and other metal	67	57
Other non-classified	82	65

Table 2.5: SEC for industrial space heating by construction year of building and building type (Biere 2014)

	Production Buildings	Office Buildings
Construction year	**SEC in kWh/m²**	**SEC in kWh/m²**
1950-1959	243	270
1960-1969	243	240
1970-1979	243	180
1980-1989	213	140
1990-1999	151	120
2000-2009	90	100
2010-2019	29	55

$$FED_{c,s,b} = EMP_{c,s} * EMPArea_{c,s,b} * SEC_b * EH(C)I_c * ShareCA \quad (2)$$ [16]

As there are no comprehensive statistics about floor area in industrial subsectors, we calculate this based on employment in each subsector (*EMP*) (Eurostat 2016-1) and the specific floor area per employee (*EMPArea*) (Biere 2014). The specific energy consumption for heating purposes (Table 2.5) differentiates two building types and seven age classes (Biere 2014). The European heating (and respectively cooling) index *EHI*, *ECI*[17] (Werner 2015) introduces differences in SEC among countries. For cooling, we include an additional estimation about the share of cooled floor area (*ShareCA*)[18]. Indices depict country (*c*), building type (*b*) and subsector (*s*). Since data on space heating and cooling in industry are generally scarce, the results are calibrated[19] using top-down values given by Eurostat (2007), while retaining subsectoral information about the distribution.

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16 The analysis presented here only comprises one base year, so there is no temporal dimension included. When used in scenario analysis, both the employment data ($EMP_{c,s}$) and the specific energy demand of the buildings ($SEC_{c,b}$) may change each year.

17 See supplementary data for values.

18 See supplementary data for values.

19 See supplementary data for values and details on data origin.

2.3 Results

We present our disaggregated energy balance of heating and cooling demand, focusing on the dimensions added to the Eurostat energy balance: temperature level and application (process heat, space heat, cooling). The heterogeneity among subsectors already presented in Figure 2.1 is accompanied by heterogeneity at process level, which we present for the iron and steel industry in Figure 2.3. It shows the share of energy used by individual processes in the subsector. Note that this is a result of the bottom-up calculation and as such not calibrated. The earlier mentioned restrictions regarding bottom-up coverage apply to this (and each result presented at process level). The very heterogeneous distribution of process shares highlights the fact that the results benefit from process differentiation among countries and that the assumption of identically distributed subsectors may not be suitable for all subsectors and countries. This is amplified in subsectors with many processes and products, like non-ferrous metals (Figure 2.4).

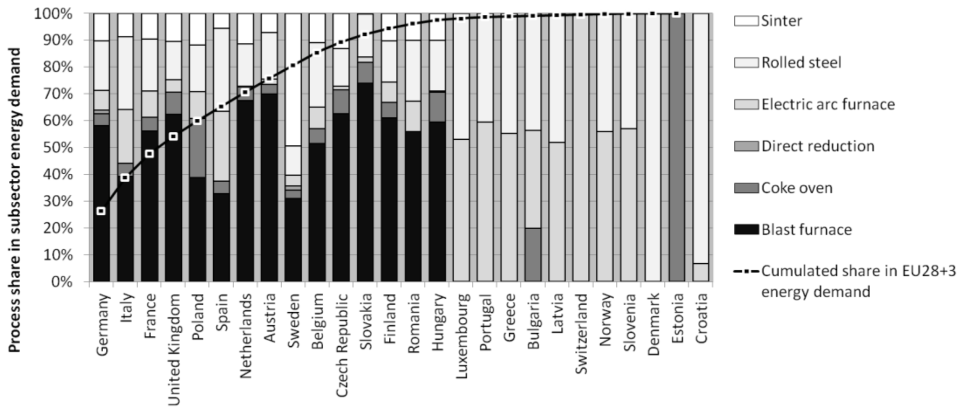

Figure 2.3. Share of processes in the iron and steel subsector FED by country, cumulated share of country's FED in EU28+3 FED

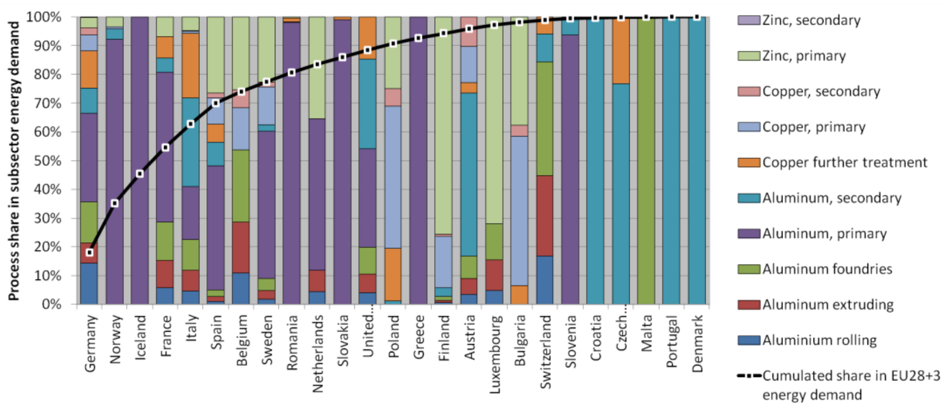

Figure 2.4: Share of processes in the non-ferrous metals industry FED by country, cumulated share of country's FED in EU28+3 FED

Temperature distribution

Of the 1035 TWh of process heat above 500°C in the EU28+3, 96% are used in the three subsectors iron and steel, basic chemicals and non-metallic minerals, with iron and steel alone contributing 48% (493 TWh) (

Figure 2.5). Basic chemicals and non-metallic minerals follow with 25% (260 TWh) and 23% (240 TWh), respectively. This is mainly caused by the combination of high absolute energy demand and high temperature level, which is found in the following processes: blast furnaces, sinter, coke ovens and electric arc furnaces (iron and steel), clinker burning (non-metallic minerals) and ammonia and ethylene production (basic chemicals). The finding that these processes contribute the most to the overall high temperature demand is consistent for the EU28+3 as a whole. Note that this still varies for individual countries; there are countries, for example, that do not engage in blast furnace operations (see also Figure 2.3). Process heat demand between 100°C and 500°C, which we assume to be the typical temperature range for steam systems, is most prevalent in the paper and printing subsector (217 TWh) as well as in other industries (203 TWh) that were not subject to detailed modelling at process level and whose results are therefore less reliable. Notable other subsectors in this respect are non-metallic minerals (82 TWh), food, beverages and tobacco (78 TWh) and basic chemicals (51 TWh). Low-temperature (<100°C) process heating (228 TWh), characterized by the use of hot water, is mostly used in chemicals (34%, 78 TWh), food, beverages and tobacco (27%, 61 TWh), paper, pulp and printing (13%, 29 TWh) and other industries (11%, 26 TWh).

In absolute terms, process and space cooling are almost negligible compared to heat demand (about 100 TWh compared to about 2300 TWh). Approximately 75 % of the total cooling system stock (about 73,000 cooling systems) in industry is located in seven countries: Germany, France, Italy, the Netherlands, Poland, the UK and Spain. Space cooling is mainly used in the Mediterranean countries of Italy, France, Spain, Portugal and Greece, and only to a very low extent in the northern European countries. However, there are significant differences concerning the process cooling demand among industrial sectors, as presented in Figure 2.6: Very low temperatures (<-30°C) occur mainly in basic chemicals (20 TWh) in the context of air separation. A very small proportion of low-temperature cooling demand is found for example in research and development processes of different industry branches. Notable other cooling demand ranging from 0°C-15°C (66 TWh) exists in food, beverages and tobacco (46 TWh), with the other subsectors combined adding up to only 19 TWh. Space cooling amounts to 12 TWh (see also Table 2.6).

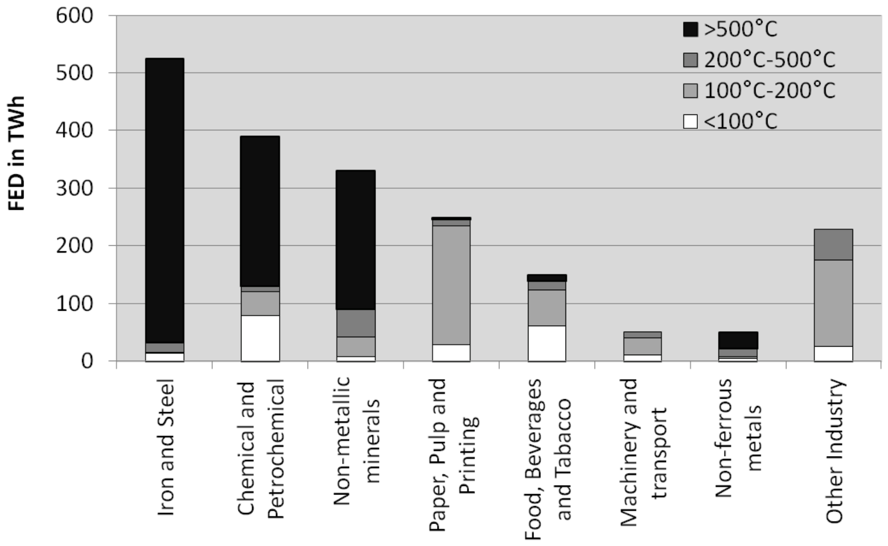

Figure 2.5: Industrial process heat demand by subsector and temperature level, EU28+3

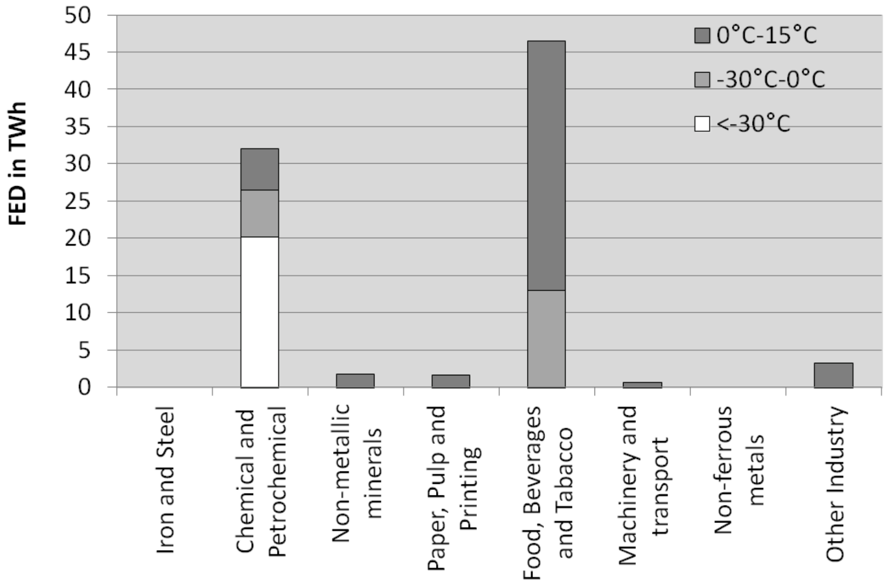

Figure 2.6: Industrial process cooling demand by subsector and temperature level, EU28+3

By adding the process-dimension, we can investigate the most important processes in terms of a high share of bottom-up-explained energy demand in total top-down energy demand. To define "high share", we arbitrarily set a limit of at least 1% of the bottom-up explained heating demand (which is approx. 90% of total top-down energy demand, 2078 TWh)). This is true for 25 individual processes, which together make up 87% of the BU-explained energy demand. Among the other processes are those with low specific energy demand (e.g. primary and secondary zinc production), low activity (e.g. semidry clinker calcination) or those mainly using electricity in applications like mechanical energy (e.g. mechanical pulp) and electrolysis[20]. Figure 2.7 shows the most relevant processes in terms of absolute energy demand with their bottom-up (BU) process heat demand and temperature distribution. We can observe that processes with high energy demand (absolute and specific) also tend towards high temperatures (>500°C)[21], with the notable exception of paper production, which shows rather average SEC (around 7 GJ/t) but high activity as a mass product. In the process, mostly steam and hot air of medium temperature are used to dry the paper rolls. Steel production, especially the blast furnace route (see e.g. Arens et al. 2016, Worrell et al. 2008 for technology descriptions), dominates high temperature demand due to both its high specific energy demand (around 20 GJ/t crude steel) and high production quantities (170 Mt in the EU28 2014, (World Steel Association 2016)). Other important processes belong to the chemical, non-metallic minerals, non-ferrous metals and food industries.

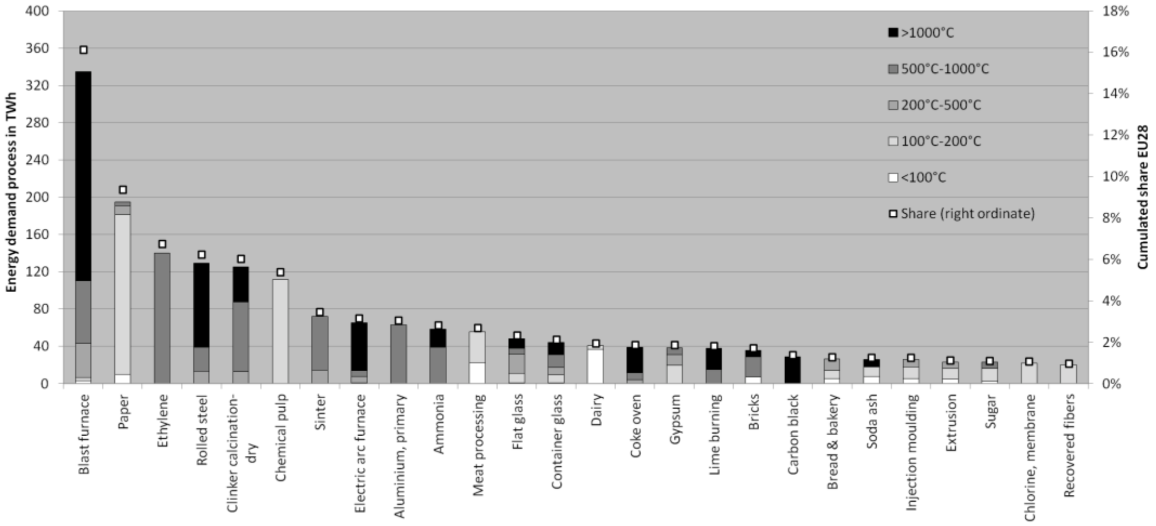

Figure 2.7: Selected industrial processes, their BU process heat demand, temperature distribution and share in total industrial BU process heat (right ordinate) in the EU28+3

20 For electrolysis, we included shares of electricity use as process heat, depending on the specific process description. Since, for example, electrolysis in the primary production of aluminium in the Hall–Héroult process requires a temperature of around 950°C, we assign approx. 2.5 GJ/t electricity use as process heat. While the theoretical minimum would be approx. 0.8 GJ/t, special conditions of the process induce heat losses (U.S.Department of Energy 2008; Nowicki and Gosselin 2012). The distinction between process heat in our definition and process-specific electricity use is therefore not trivial.

21 Of the 25 processes presented, the 10 biggest include 8 processes that mainly or exclusively use high temperature heat above 500°C.

Table 2.6: Industrial process and space heating/cooling demand by country and temperature level EU28+3 (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016)

TWh	Space heating	Process heat <100°C	Process heat 100°C-200°C	Process heat 200°C-500°C	Process heat >500°C	Heating	Process cooling <-30°C	Process cooling -30°C- 0°C	Process cooling 0°C-15°C	Space cooling	Cooling	Heating and cooling
Austria	13.4	3.3	22.0	5.3	35.5	**79.4**	0.7	0.4	0.7	0.1	**1.9**	**81.3**
Belgium	13.9	7.1	14.8	6.7	42.4	**84.8**	1.6	0.9	1.9	0.1	**4.5**	**89.3**
Bulgaria	5.4	5.1	3.5	1.5	6.9	**22.5**	0.3	0.2	0.4	0.2	**1.0**	**23.5**
Switzerland	2.0	2.8	6.1	2.2	9.6	**22.7**	0.1	0.3	0.6	0.0	**1.0**	**23.7**
Cyprus	0.1	0.1	0.2	0.2	0.9	**1.5**	0.0	0.0	0.1	0.0	**0.1**	**1.7**
Czech Republic	9.4	7.7	13.1	5.5	30.3	**66.0**	1.0	0.4	0.8	0.1	**2.3**	**68.3**
Germany	58.3	64.3	92.1	34.6	251.1	**500.3**	5.3	3.9	9.2	0.1	**18.5**	**518.8**
Denmark	3.5	3.1	5.6	1.8	4.3	**18.4**	0.0	0.3	0.8	0.0	**1.2**	**19.6**
Estonia	1.6	0.4	1.3	0.4	0.9	**4.5**	0.0	0.0	0.1	0.0	**0.2**	**4.7**
Greece	4.2	2.7	5.6	2.0	9.7	**24.2**	0.1	0.2	0.5	0.7	**1.4**	**25.6**
Spain	31.4	4.4	45.3	14.5	82.3	**177.8**	1.1	1.5	3.8	3.5	**9.9**	**187.7**
Finland	6.2	16.1	45.7	5.3	15.6	**89.0**	0.8	0.4	1.1	0.0	**2.2**	**91.2**
France	46.8	8.6	38.5	15.8	97.7	**207.3**	0.7	2.7	6.3	1.7	**11.3**	**218.7**
Croatia	1.3	1.4	2.9	1.1	3.6	**10.3**	0.0	0.1	0.2	0.1	**0.4**	**10.7**
Hungary	4.7	3.8	2.3	1.1	9.3	**21.2**	0.1	0.2	0.4	0.1	**0.8**	**22.0**
Ireland	3.9	1.4	4.5	1.7	5.3	**16.8**	0.0	0.3	0.6	0.0	**1.0**	**17.8**
Iceland	0.4	0.1	0.1	0.0	1.5	**2.2**	0.0	0.0	0.3	0.0	**0.3**	**2.5**
Italy	47.7	27.9	26.5	16.6	117.7	**236.4**	3.2	2.0	5.2	4.5	**14.9**	**251.3**
Lithuania	1.7	2.7	1.7	0.6	2.2	**8.8**	0.0	0.1	0.2	0.0	**0.3**	**9.2**
Luxembourg	0.6	0.1	0.5	0.7	3.9	**5.7**	0.0	0.0	0.1	0.0	**0.1**	**5.8**
Latvia	1.4	0.5	3.0	1.0	2.2	**8.2**	0.0	0.0	0.1	0.0	**0.1**	**8.3**
Malta	0.0	0.0	0.0	0.0	0.0	**0.1**	0.0	0.0	0.0	0.0	**0.0**	**0.1**
Netherlands	14.9	17.4	21.1	7.6	66.5	**127.6**	2.3	1.2	2.4	0.1	**5.8**	**133.4**
Norway	5.6	0.5	5.0	1.1	14.8	**27.0**	0.2	0.5	0.9	0.0	**1.5**	**28.6**
Poland	10.0	15.4	29.5	10.7	62.0	**127.6**	1.4	1.1	2.4	0.1	**4.9**	**132.5**
Portugal	6.7	4.0	15.0	2.5	13.1	**41.4**	0.1	0.3	0.6	0.6	**1.7**	**43.0**
Romania	10.4	4.0	8.5	4.0	33.1	**60.0**	0.4	0.3	0.7	0.0	**1.4**	**61.4**
Sweden	7.6	4.9	49.6	7.0	15.4	**84.4**	0.1	0.4	1.0	0.0	**1.5**	**85.9**
Slovenia	1.7	0.6	2.2	0.5	3.6	**8.6**	0.0	0.0	0.1	0.0	**0.2**	**8.8**
Slovakia	6.1	1.7	4.0	0.9	26.7	**39.4**	0.4	0.1	0.2	0.1	**0.9**	**40.4**
United Kingdom	25.6	16.4	61.0	22.1	66.3	**191.3**	0.3	1.7	4.5	0.0	**6.6**	**197.9**
EU28+3	**346.3**	**228.1**	**531.2**	**175.3**	**1034.6**	**2315.6**	**20.1**	**19.4**	**46.1**	**12.4**	**98.0**	**2413.6**

If we turn away from processes and focus on end-uses, we can observe a relatively stable temperature distribution among the larger countries (Figure 2.8, Table 2.6). Robust findings include high temperature shares (process heating above 500°C) between 40% and 50%, which are found in 13 countries and account for approx. 80% of the total energy demand for heating and cooling (H/C). Medium temperature (200-500°C) energy demand between 5% and 10% can be observed for 21 countries and 86% of the total H/C demand. There are stronger variations in process heating shares between 100°C and 200°C and below 100°C, which range from 4% to 50% and 4% to 29%, respectively. Notable exceptions are Iceland, Cyprus and Malta, which show remarkably high relative cooling demand shares. This is probably caused by low data availability, sometimes limited to electricity or certain subsectors in terms of top-down energy demand[22]. This also applies to activity data, limiting the reliability of our results for these countries in general. Another conspicuous result is the high share of process heating between 100 and 200 °C in Sweden and Finland. This can be explained by the high importance of the pulp and paper industry in these countries, accounting for 33% (58 TWh) and 27% (50 TWh) of their total heating demand, respectively. Slovakia shows a high share of high temperature energy demand, which is caused by the iron and steel industry with 21.9 TWh above 500°C (54% of the country's total reported industrial energy demand). The same is true for Luxembourg (3.1 TWh above 500°C, 53% of the reported total). Compared to the EU28+3, Germany seems to be a good proxy regarding overall end use; but country-specific structures can still have a strong impact.

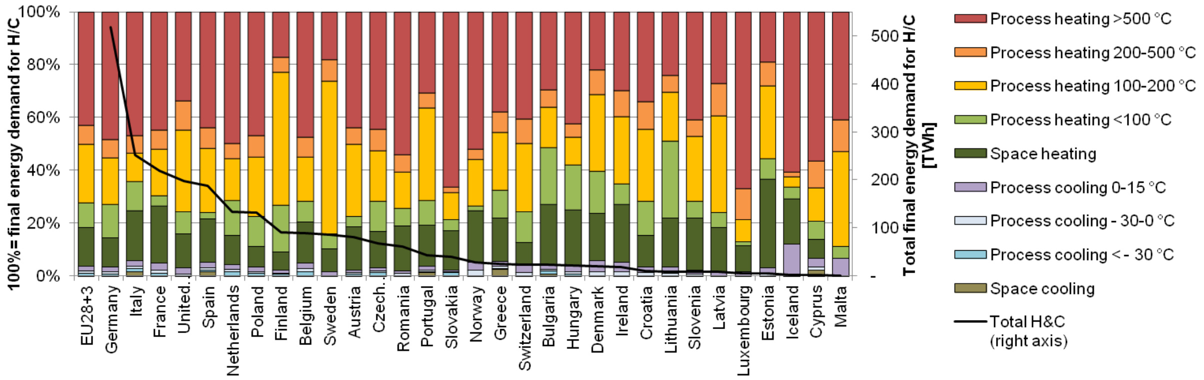

Figure 2.8: Temperature share and final energy demand for industrial heating and cooling by country for the EU28+3 (Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer 2016)

Energy carriers

According to our model results[23], the most frequently used energy carriers for industrial heating and cooling (Figure 2.9) are natural gas (935 TWh, 39% of total), coal (415 TWh, 17%), other fossils (243 TWh, 10%), biomass (216 TWh, 9%), fuel oil (208 TWh, 9%), district heat (184 TWh, 8%) and electricity (173 TWh, 7%). Germany, Italy, France, the United Kingdom and Spain account for 57% (1374 TWh) of the total heating and cooling demand of the EU28+3 (2413 TWh), while the 14 smallest countries in terms of energy use together account for 10% (253 TWh).

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22 For example, for 2015, Eurostat's energy balances (Eurostat 2016-2) show 46 ktoe (0.53 TWh) industrial energy demand for Malta, with 36 ktoe (0.42 TWh) of electricity. This proportion is very different from the ones we observe in other economies. The model is not well suited to deal with this, whether the cause is a real difference in economies or a statistical issue.

23 The general distribution of energy carriers can already be derived from Eurostat (2016-2). The main difference in these results is that they refer to heating and cooling instead of total energy demand. This does, however, mainly affect electricity, as fuels are assumed to be used for heating uses only.

FORECAST uses an average energy carrier share per subsector and country (i.e. not per process), based on the respective shares in the subsector's energy balance (Eurostat 2016-2). The means that the subsector's energy carrier distributions are automatically meet the energy balance. At the same time, the energy carrier use cannot be analysed on process level. Thus, for Figure 2.10, it has to be noted that the temperature distribution refers to subsector-use of energy carriers. We can still observe that the distribution of energy carriers to temperature levels generally confirms expectations: Coal and electricity are used for high temperature energy demand (steel industry, electrolysis), natural gas is used in all temperature levels and biomass is used in low temperature subsectors (e.g. paper production). The share of high temperature use of waste is most likely connected to its use in clinker production.

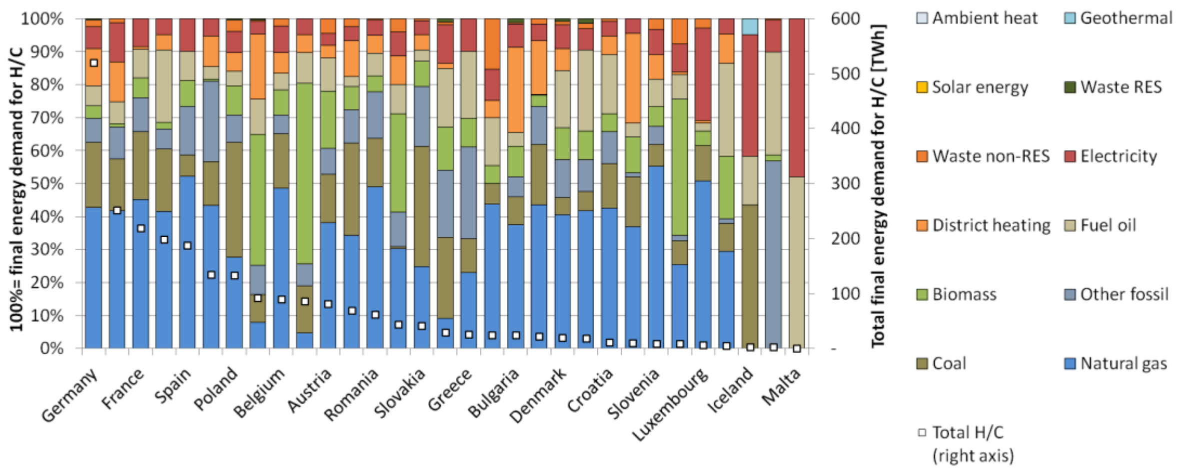

Figure 2.9: Energy carrier share and final industrial energy demand for heating and cooling by country for the EU28+3 (model results based on Eurostat 2016-2)

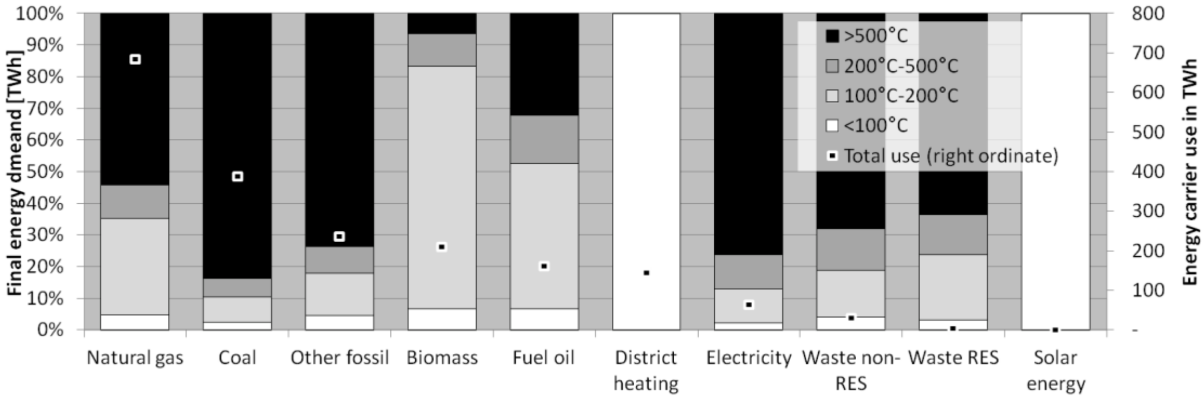

Figure 2.10: Energy carrier use by temperature for industry in the EU28+3

2.4 Discussion

Results compared to Eurostat energy balance: bottom-up coverage

The bottom-up results for space and process heating/cooling (plus non-heat use) do not match the energy balance (Eurostat 2016-2) in most cases, because of general data imperfections and because not all industrial processes are covered. We call the degree to which the bottom-up (BU) values match the top-down (TD) energy balance "*bottom-up coverage*" (BU-coverage). A value of "1" means that the BU-values are in line with the energy balance. Lower values indicate energy demand, which is not accounted for in the BU-calculation. We assume that this gap occurs mainly due to energy use in processes not covered in the model. Subsidiary temperature distributions at subsector level (Figure 2.11) are assigned to this energy use. Since these distributions lack the level of detail of the BU-calculation, achieving high BU-coverage is a quality criterion of the model.

Bottom-up coverage values greater than 1 can occur if the SEC or the production of processes is overestimated. In these cases, the respective overestimated processes might be overrepresented in their subsector.

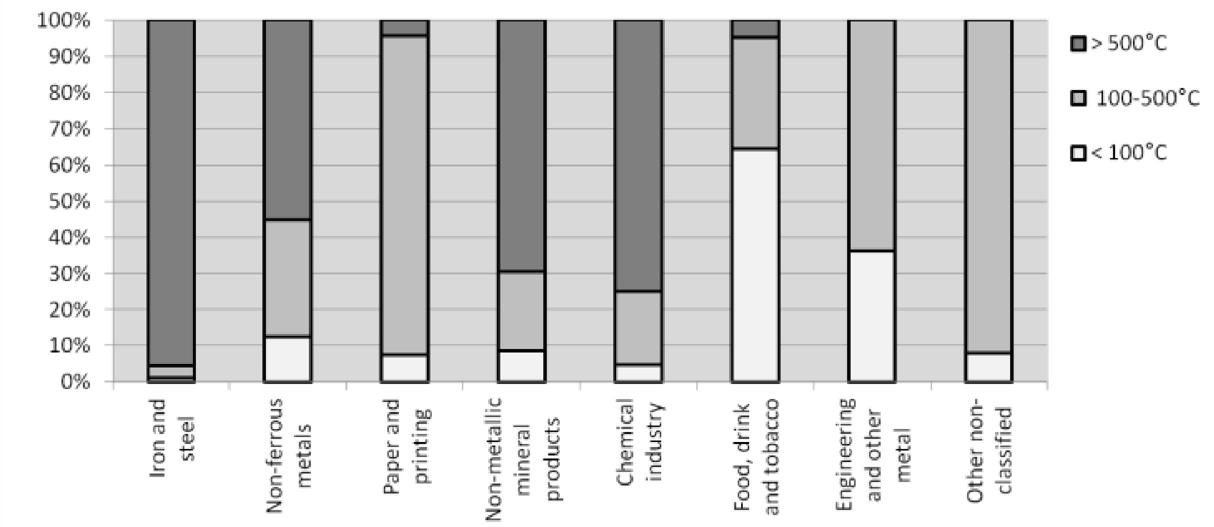

Figure 2.11: Subsidiary industrial subsector temperature distribution (used for energy demand not covered by bottom-up calculation, assumptions)

The dimensions of the BU-coverage are subsectors (e.g. iron and steel, chemical industry) and countries (Figure 2.12, Figure 2.13, Figure 2.14, Figure 2.15). Note this includes only heating and cooling-related energy demand (i.e. excludes electricity use for lighting, mechanical energy etc.). The aggregated BU-coverage (across countries or subsectors) is calculated using final energy demand (FED)-weighted averages of the lowest level of aggregation (individual subsector and country)[24]. In

24 This means that countries' and subsectors' BU-coverage is weighted by the final energy demand (FED) of the respective aggregated dimension: Countries with low FED contribute less to BU-coverage in Figure 2.4; subsectors with low FED contribute less to BU-coverage in Figure 6.

general, the energy demand in the iron and steel subsector is somewhat overestimated (Figure 2.12, Figure 2.15). This is most likely related to the use of derived gases (e.g. stack gas, converter gas) in power plants and to autoproducers of electricity, whose balance in Eurostat and national energy balances is not necessarily compatible with technology-focused bottom-up estimations. The chemical industries are underestimated because several processes here are too small to include in FORECAST. The BU-values of “Other non-classified” and “Engineering and other metal” do not include processes for the same reason, so their BU-values consist solely of space heating (i.e. no bottom-up processes are calculated for these subsectors). In Figure 2.12, Figure 2.13, Figure 2.14, Figure 2.15, the right ordinates show the cumulated share of the displayed categories. Figure 2.13 reveals that the apparently good average coverage for the “Engineering and other metal”-subsector on the EU28+3-level in Figure 2.12 is a rather random result. In fact, many countries, among them the three biggest energy users in this subsector (Germany, Italy, France), which together account for 56% of the EU28+3`s energy demand, show a BU-coverage of around 0.5, while some smaller countries’ contributions in this subsector are overestimated. As our methodology relies on technology-based process descriptions, it yields little or no benefit in subsectors that are characterized by a huge variety of heterogeneous products like the engineering sector. In total, the energy demand in subsectors not readily accessible to our approach amounts to 700 TWh or 22% of the industrial energy demand in the EU28 in 2014 (Eurostat 2016-2).

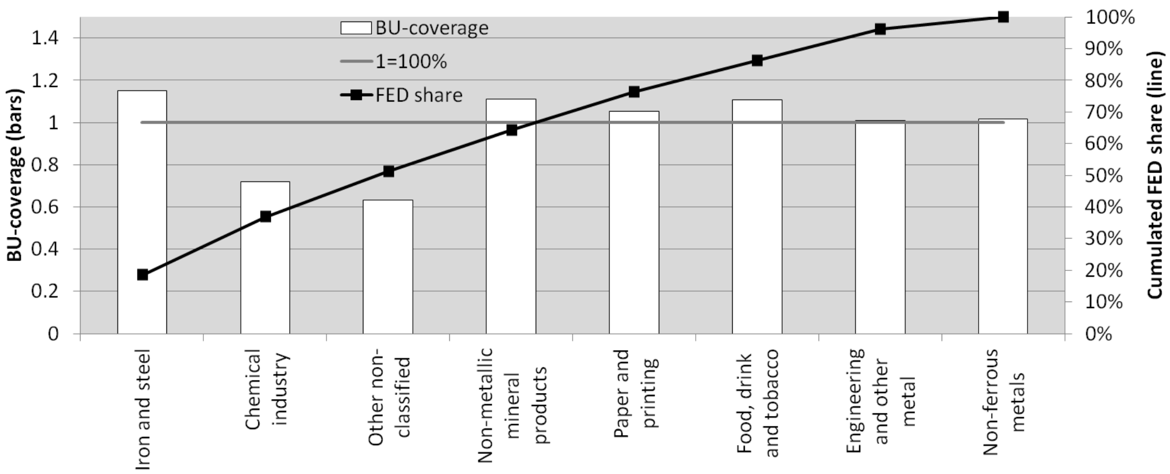

Figure 2.12: Bottom-up coverage of industrial heating and cooling demand by subsector for EU28+3, 1=100%, right ordinate: cumulated FED share

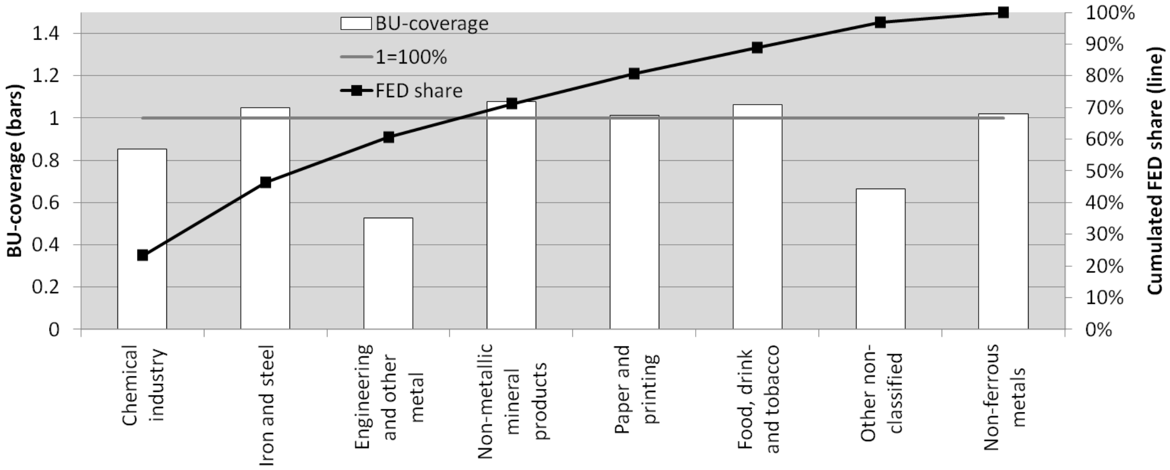

Figure 2.13: Bottom-up coverage of industrial heating and cooling demand by subsector for Germany, 1=100%, right ordinate: cumulated FED share

We observe that the seven biggest countries, accounting for approx. 65% of FED, have a BU-coverage of about 90% (Figure 2.14), which we consider a good value (100% is generally too high due to missing processes). Countries with smaller FED, however, tend to deviate more from this target, which can be explained by the higher relative impact of both missing processes and errors in technological and economic assumptions[25] (e.g. SEC for processes, area for space heating). A detailed look at the iron and steel subsector shows that the overestimation via the bottom-up approach is structural (Figure 2.15). At the process level, we found that this is mostly accountable to the energy demand of pig iron production (blast furnaces), which is thus overrepresented in this subsector. However, the resulting error regarding the temperature profile is likely to be minor, since blast furnaces use the vast majority of energy anyway. An overview of the two relevant dimensions country and subsector (Table 2.7,ordered by heating demand) confirms the impression that the bottom-up coverage[26] is better in countries and subsectors with higher overall heating demand (top left) than in smaller countries and subsectors (lower right). However, the 20 countries with the lowest energy demand only account for 15% of the total EU28+3 energy demand (Figure 2.14).

25 Smaller countries tend to have a less complete process portfolio. This has the effect of enhancing any errors in the assumptions about processes that do exist. Additionally, outliers of specific energy consumption are accorded higher weight.

26 Note that Ireland (5) and Estonia (10) have very poor BU-coverage inFigure 2.15, indicating inconsistency between the energy balance and production statistics.

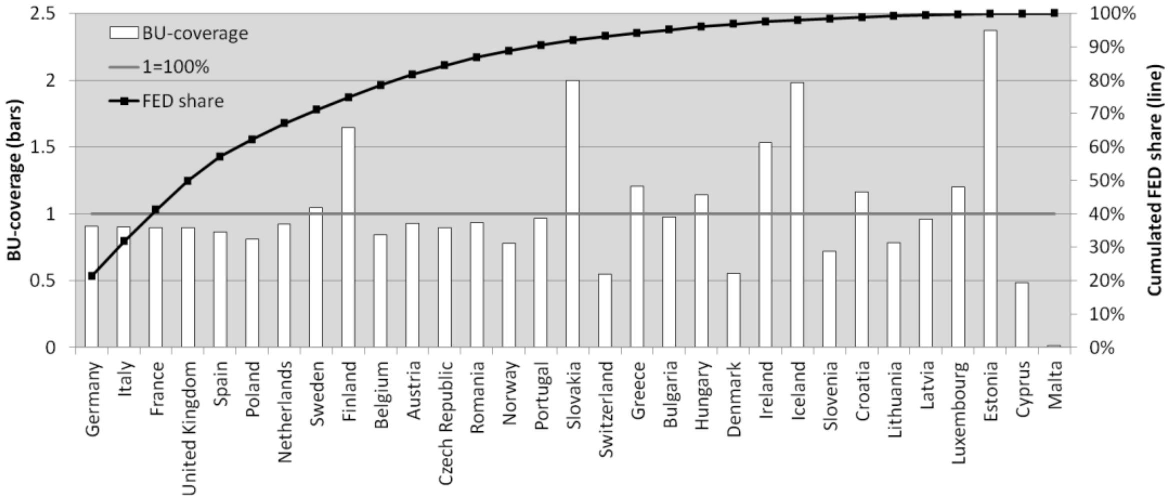

Figure 2.14: Bottom-up coverage of industrial heating and cooling demand all subsectors by country, 1=100%, right ordinate: cumulated FED share

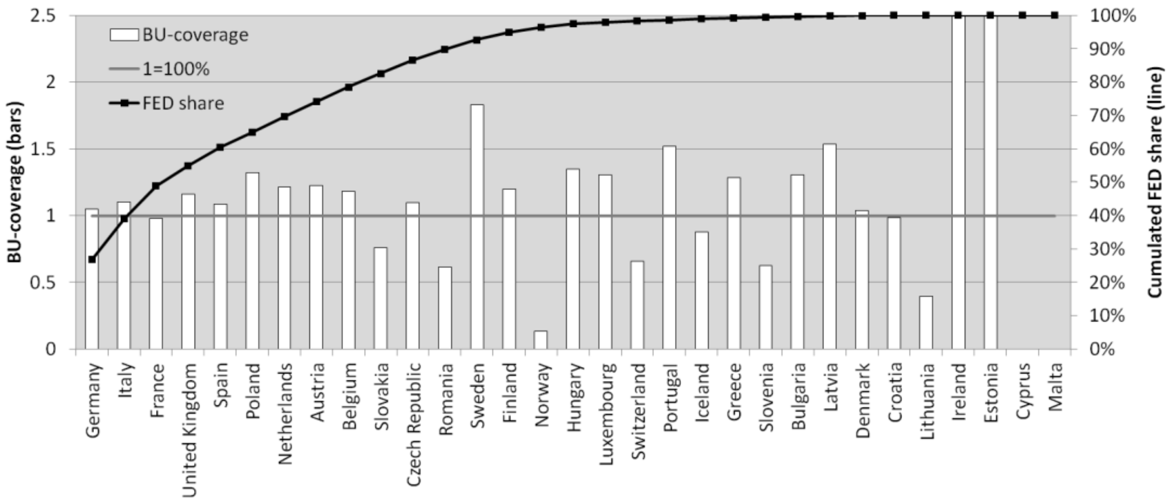

Figure 2.15: Bottom-up coverage of industrial heating and cooling demand Iron and steel subsector by country, 1=100%, right ordinate: cumulated FED share; BU-coverage Ireland 5, Estonia 10

Table 2.7: Bottom-up coverage by country and industrial subsector (darker fields are closer to the expected value of approx. 0.9)

Country	Iron and steel	Chemical industry	Non-metallic mineral proc	Paper and printing	Non-ferrous metals	Food, drink and tobacco	Engineering and other me	Other non-classified	Country	Iron and steel	Chemical industry	Non-metallic mineral proc	Paper and printing	Non-ferrous metals	Food, drink and tobacco	Engineering and other me	Other non-classified
Germany	1.0	0.9	1.1	1.0	1.0	1.1	0.5	0.7	Switzerland	0.7	0.1	0.8	0.9	0.9	0.4	0.4	0.5
Italy	1.1	0.8	1.0	0.9	1.2	1.0	0.6	0.8	Greece	1.3	1.2	0.6	1.3	0.3	0.7	3.9	0.4
France	1.0	1.1	0.8	1.2	1.0	0.7	0.5	0.7	Bulgaria	1.3	0.5	1.3	0.5	0.8	1.5	1.2	0.8
United Kingdom	1.2	0.9	1.0	1.0	0.6	1.1	0.8	0.3	Hungary	1.3	1.8	1.0	1.1	0.1	1.0	0.7	0.9
Spain	1.1	0.3	0.9	1.2	0.7	1.3	1.2	0.5	Denmark	1.0	0.2	0.8	0.4	0.0	0.7	0.5	0.3
Poland	1.3	0.6	1.3	0.9	0.6	0.7	0.3	0.4	Ireland	4.9	0.4	1.1	1.6	0.0	1.1	0.5	0.3
Netherlands	1.2	0.2	1.3	1.2	1.2	0.7	1.3	0.7	Iceland	0.9	0.0	0.0	0.0	25.1	0.0	0.0	5.8
Sweden	1.8	0.2	1.8	1.0	1.1	1.3	1.1	0.2	Slovenia	0.6	0.4	1.4	1.0	0.4	1.1	0.5	0.4
Finland	1.2	0.8	2.0	0.9	0.8	2.6	5.1	0.8	Croatia	1.0	1.1	1.2	1.7	1.8	0.8	2.1	0.5
Belgium	1.2	0.4	1.0	1.0	1.4	0.7	1.0	0.5	Lithuania	0.4	0.8	0.7	1.2	0.3	1.1	1.2	0.6
Austria	1.2	0.8	0.9	1.0	1.1	1.1	1.1	0.4	Latvia	1.5	0.5	0.4	2.0	0.2	1.3	1.2	0.3
Czech Republic	1.1	0.6	1.2	0.9	1.1	1.2	0.8	0.5	Luxembourg	1.3	0.5	1.6	2.1	0.0	0.7	2.8	0.5
Romania	0.6	0.4	1.5	1.8	0.0	1.4	0.9	0.7	Estonia	10.0	0.5	0.6	1.0	0.2	1.2	0.7	0.3
Norway	0.1	0.8	1.2	1.1	1.0	1.1	1.1	0.3	Cyprus	0.0	0.3	1.0	0.6	0.6	0.9	0.9	0.2
Portugal	1.5	0.7	0.8	0.9	0.6	1.3	1.1	0.6	Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Slovakia	0.8	0.9	1.8	1.2	1.6	3.9	3.6	3.5									

Considering these results, we can assume that the process-based approach represents the real industrial structure of the countries and subsectors with the highest energy demand well enough to form a relevant picture of their temperature profiles. Differentiating processes thus enhances the country-specific patterns of industrial energy use and does not create unreasonable distortions of subsectoral energy demand compared to top-down sources. In smaller countries and subsectors, the added value of the process-based approach is reduced considerably. Furthermore, the approach reflects the chemical industry as a major but strongly heterogeneous energy user less accurately than other subsectors.

Results compared to selected end-use balances

Among the available end-use balances mentioned, we chose those of the United Kingdom and Austria as benchmarks for our results[27].

The United Kingdom's end-use balance ECUK (Department for Business, Energy & Industrial Strategy 2016-1) comprises the dimensions subsector, end-use and energy carrier. Since the absolute

27 The German end-use balance 2012 is not a suitable candidate for comparison as it was compiled with the support of the same model we use here.

values match neither those of Eurostat (2016-2), nor our results nor those of the aggregated energy balance DUKES (Department for Business, Energy & Industrial Strategy 2016-2) for reasons of methodology and scope, we only compare the relative shares of the end uses. In the ECUK reports, these are high temperature (i.e. mainly iron and steel, non-metallic minerals), low temperature (i.e. mainly food, chemical, paper), and drying and separation (i.e. mainly paper). Detailed information on the definitions can be found in (Department for Business, Energy & Industrial Strategy 2016-3). Table 2.8 and Table 2.9 show the allocation we assumed for temperature levels and subsectors based on the information available there.

Table 2.8: Assumptions for temperature level relation ECUK/FORECAST

ECUK	FORECAST
High temperature	>500°C
drying/separation	200°C-500°C
Low temperature	<200°C
Space heating	Space heating
Refrigeration	All cooling
Other	-

Table 2.9: Industrial subsector relation ECUK-FORECAST, *(...)* indicate shortened names

ECUK	FORECAST
Basic metals	Iron and steel, non-ferrous metals
Coke and refined petroleum products	Iron and steel, non-ferrous metals
Food products	Food, beverages and tobacco
Beverages	Food, beverages and tobacco
Tobacco products	Food, beverages and tobacco
Chemicals and chemical products	Chemicals
Non-metallic mineral products	Non-metallic minerals
Paper and paper products	Paper
Printing and publishing (…)	Paper
Machinery (…)	Machinery and Transport
Motor vehicles (…)	Machinery and Transport
Other transport equipment	Machinery and Transport
Rubber and plastic products	Other industry
Textiles	Other industry
Wearing apparel	Other industry
Wood (…)	Other industry
Other manufacturing	Other industry
Electrical equipment	Other industry
Furniture	Other industry
Leather and related products	Other industry
Fabricated metal products (…)	Other industry
Computer (…)	Other industry
Other mining and quarrying	Other industry

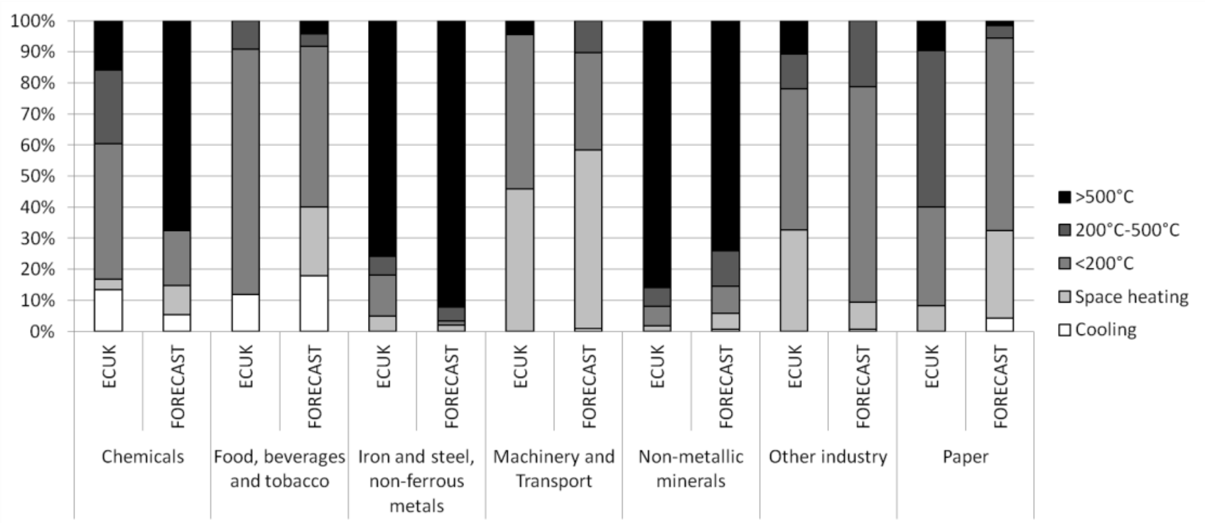

Figure 2.16: Temperature shares by industrial subsector in the United Kingdom, ECUK and FORECAST (data from Department for Business, Energy & Industrial Strategy 2016-1, FORECAST, own illustration, reallocated subsectors and temperature levels according to Table 2.8 and Table 2.9)

While the overall temperature share patterns of the studies are similar (high and low temperature dominated subsectors, Figure 2.16), we can observe differences in the medium-temperature range that are most likely caused by the approximate temperature allocation given in Table 2.8. The distinctions made between >200°C and 200°C-500°C and 200°C-500°C and >500°C are not very sharp at the edges, possibly creating overlaps due to different process definitions among studies. Additionally, there are notable anomalies in three subsectors: ECUK allocates no space heat to the food subsector; possibly due to installations generating both space heat and low temperature process heat; and the ECUK-subsector *basic metals* (SIC 2007: 24) includes both iron and non-ferrous metals, which blurs their respective temperature profiles considerably. The third anomaly is the low temperature share in the chemical subsector, which is much higher in ECUK. Based on the information available, we can only assume that this is mainly steam generation, which would cover a much wider temperature range than assumed in Table 2.8. Thus, the model results *might* be a plausible fit to the ECUK-temperature distribution. However, there is no certainty due to the methodological differences mentioned.

The Austrian end-use balance (Statistik Austria 2016-1) is based on the national overall energy balance (Statistik Austria 2016-2) and is, in most parts, directly comparable to Eurostat. The industrial subsectors are comparable, and the energy carrier categories used are similar to those of Eurostat (2016-2). However, the iron and steel subsector has a different definition. Energy demand in blast furnaces is accounted as energy conversion in the overall energy balance (Statistik Austria 2016-2) and not included in the detailed end-use analysis (Statistik Austria 2016-1). For our purpose of comparing results, we assigned the entire demand of the energy carriers coke, coking gas and blast furnace gas balanced in the energy balance to *high temperature demand* (>500°C), as these energy carriers are closely related to blast furnaces (and thus to high temperature). The end-use balance adds the dimension of application (space heating, steam generation, furnaces and several non-heat uses) to the energy balance. We assigned these applications to temperature levels as shown in Table 2.10.

Table 2.10: Assumption on temperature level relation Statistik Austria (2016-1) to FORECAST

Statistik Austria	FORECAST
Space heating	Space heating
Steam generation	200°C-500°C
Furnaces	>500°C

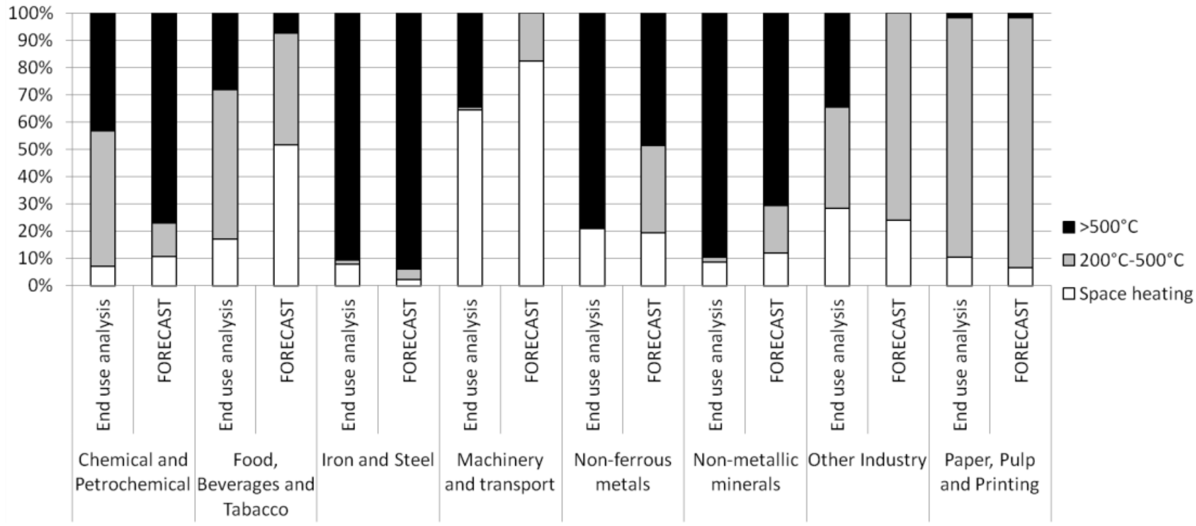

Figure 2.17: Temperature shares by industrial subsector in Austria, end-use analysis (Nutzenergieanalyse, Statistik Austria (2016-1)) and FORECAST

We observe general similarities for the subsectors other industry, non-ferrous metals, iron and steel and paper, pulp and printing, although the temperature range suitable for steam generation is not explicitly defined (Figure 2.17, compare Table 2.10). This creates uncertainty about the profile for non-ferrous metals and non-metallic minerals. The Austrian end-use analysis does not include steam generation in these subsectors, thus excluding the temperature range of 200°C-500°C *in our translation* (Table 2.10). Again, many differences in the compared temperature profiles might be explained by different allocations at the edges of temperature ranges. In “Machinery and transport” as well as “Other industry”, we do not assume any high temperature energy demand above 500°C. However, these subsectors are not calculated in detail due to their strong heterogeneity even at process level. In the food subsector, space heating and steam generation seem to be connected (similar to what we observed in the United Kingdom).

Overall, we have to concede that the comparison with ECUK and with the end-use analysis created by Statistik Austria (2016-2) do not necessarily support our results. We assume that the observed differences can be explained by different subsector and/or temperature/application definitions (as shown in Table 2.8 and Table 2.10). This highlights the fact that a common methodology and definition of the included dimensions are required for comparability.

Results compared to recent publications

To further interpret the results of our approach, we compared them with recent publications (Naegler et al. 2015; Pardo et al. 2013). Naegler et al. (2015) seems well suited to highlight the benefits of the detailed bottom-up data and the combination of empirical and modelling elements because they use a similar methodology and some of the same data sets (e.g. ISI 2013; Eurostat 2016-2). Directly comparing the absolute energy demand of our approach and two data sets of Naegler et al. (2015) at country level (Figure 2.18) shows that, in general, data set 2 (DS-2) in Naegler et al. (2015*)* seems to be a closer match to our results. This is most likely due to the use of Eurostat energy balances in each case. The remaining differences are probably caused by different assumptions about non-heating/cooling use, which is especially relevant for electricity. Note that, although our results match the Eurostat energy balance (Eurostat 2016-2) for 2012 at subsector and energy carrier level[28], there are considerable differences for some countries. In particular, there is a comparatively high absolute difference for Germany and France. Among the possible explanations, it seems plausible that this may be due to how space heating is accounted because of generally scarce data availability in industry regarding floor area as well as specific energy consumption. Another reason could be the use of electricity and how the share of electricity used for process heating is defined (see footnote on electrolysis in section *Temperature distribution*).

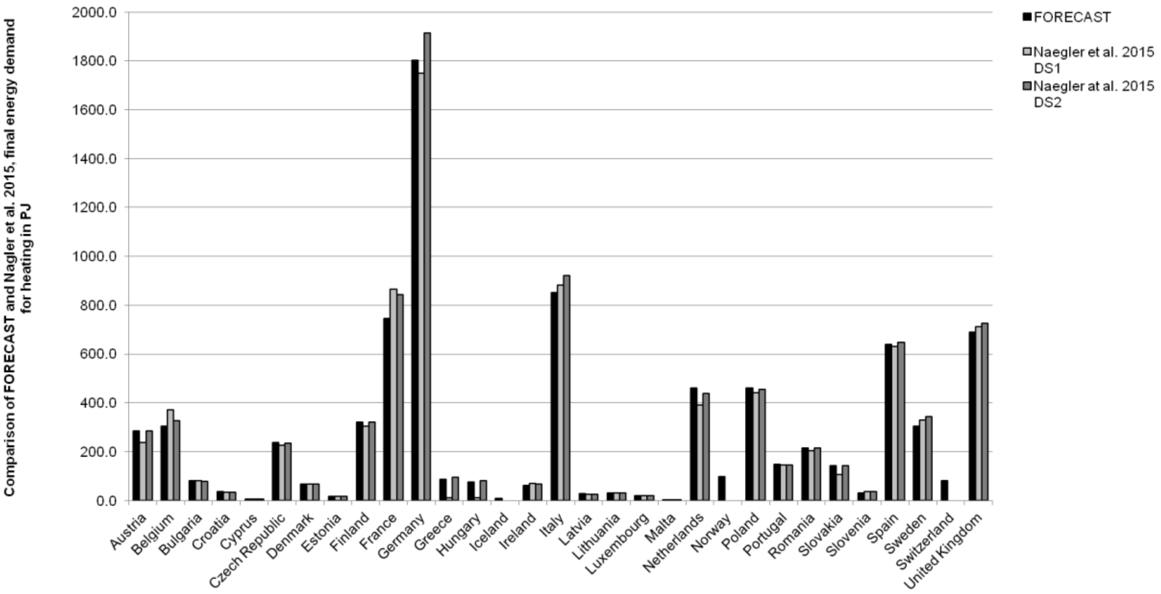

Figure 2.18: Industrial final energy demand for heating, comparison of FORECAST (EU28+3) and Naegler et al. (2015) (EU28)

Figure 2.19 compares the temperature shares used by Naegler et al. (2015), Pardo et al. (2013) and our approach. While the temperature distribution shows a similar pattern for most subsectors, there is the general trend that our process-based approach shows lower demand below 100°C than the

28 Naegler et al. (2015) claim to match the energy balance, too.

subsector-based approaches. Most characteristic for the profiles is the relevance of high temperature energy demand in minerals and metallic industries (e.g. blast furnace, cement kiln, melting furnaces), medium temperature demand in paper and printing (steam for paper production and drying) and low temperature demand in the food subsector as well as engineering and other metal and other non-classified industries. It should also be noted that we use a production-weighted average of country-specific temperature profiles in Figure 2.19 for the FORECAST-data set (since the temperature profiles are actually used at process level). It can also be observed that both subsector-based approaches, Naegler et al. (2015) and Pardo et al. (2013), tend to agree more on the temperature shares; this is most apparent in the chemical and non-metallic industries. As mentioned before in the comparison with national end-use balances, the different temperature range definitions impede comparison.

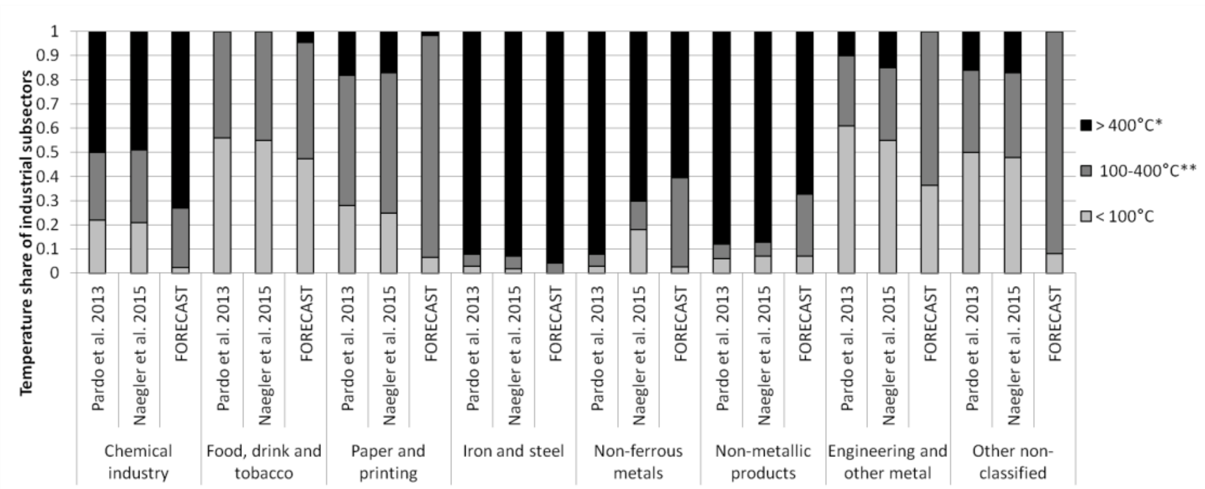

Figure 2.19: Temperature share assumptions by industrial subsector: Comparison of Pardo et al. (2013), Naegler et al. (2015) and FORECAST; FORECAST: weighted average of processes in respective subsector, * FORECAST: >500°C, ** FORECAST: 100-500°C

Methodological issues

The methodology relies on the availability of production data at process level, which is sometimes a drawback, especially for smaller countries or those with an unusual industrial structure. In addition, analysing the bottom-up coverage shows that process structure can be very diverse in some sectors (like chemicals), limiting the achievable share of bottom-up modelled industry (i.e. the *process equals process* assumption is violated or processes are neglected). For example, as of today, the ECHA (2016) lists over 15,000 products related to the chemical industry, of which 43 are produced in tonnages over 10 Mt per year. Even minor products or processes (in terms of energy demand) can still add up to a relevant share of the total energy demand. FORECAST’s focus on energy-intensive industries, which necessarily neglects others, is thus both its strength (in terms of technological explicitness) and its weakness (in terms of completeness). Detailed knowledge about processes and their key indicators (specific energy demand, temperature profile, applicable energy carriers) is essential to achieve plausible results. Apart from very general challenges regarding energy efficiency-related indicators[29] (Patterson 1996), industrial energy demand is especially difficult to capture in terms of data availability. Specialised and small processes are particularly problematic that have relatively low importance in terms of absolute energy demand and have therefore not been studied in detail. Nevertheless, it remains questionable whether increased efforts in this regard can be justified in general. Fleiter et al. (2013) found that, for Germany, the processes included in FORECAST in its present state cover up to 86% of fuel demand, with the 20 largest processes already covering around 75% (see also Figure 2.12) Further research should therefore focus on singular processes that are identified as particularly relevant in the countries (or subsectors) of interest.

Shortcomings in any of these fields (technological or economic data) result in a loss of precision, as energy demand that is not covered by the bottom-up approach is treated on an aggregated subsector level. This means that smaller processes that are not modelled in detail tend to be marginalized, even if they have greater relevance in certain countries with an unusual economic structure. This accords greater weight to the temperature distribution aggregated at subsector level, which can act as a fallback option to alleviate this drawback.

The basic assumption *process equals process*, while mostly sensible in general, ignores some differences in energy efficiency or other process characteristics that exist among countries with technological disparities (e.g. electricity use in the chemical industry is very different in France and Germany). Further research seems necessary on how technological differences among countries contribute to their process efficiency and specific energy demand, possibly linking them to more accessible data on a higher aggregation level.

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29 Patterson (1996) categorizes "persistent methodological problems": value judgements (e.g. what is useful energy), energy quality (e.g. enthalpy vs. exergy), boundaries (e.g. which input is considered to enter the energy balance, and in what quality and state?), joint production (e.g. what is the main product of a process with multiple outputs and how to assign its energy use; combined heat and power production is the most popular example), and technical/ gross efficiency.

2.5 Conclusions

Within this paper, we presented a methodology to disaggregate energy balances and add the dimensions *temperature level* and *end use* using a bottom-up energy demand model. We investigated how including processes as the lowest level of differentiation in the production process adds to temperature profiles by comparing our results with previous work based on subsectors, and introducing *bottom-up coverage* as a quality criterion for the methodology. In doing so, we generated an end-use balance for the EU28+3 in 2012 based on Eurostat's energy balance (Eurostat 2016-2). Our approach of combining bottom-up data at process level with top-down energy balances and the results for the EU28+3 presented here show promise to support energy demand research and policy design[30]. Compared to individual national energy and end-use balances, our approach has the main advantage that results are comparable due to a consistent methodology across all countries. It combines technologically explicit knowledge about processes and their individual properties needed to design targeted policies with real production values and available energy balances (Eurostat or national). As Naegler et al. (2015) point out, studying the processes applied in industrial subsectors demands details regarding their temperature profiles. We agree with their finding that a comprehensive estimation of the temperature levels of process heat demand is needed and made an effort to contribute to this (Table 2.1). The general approach that specific energy demand multiplied by production equals total energy demand is immediately evident, and the well-maintained database of processes and activities ensures high bottom-up coverage of many large and most smaller countries.

30 For example by providing a more detailed picture of waste heat potentials, the use of temperature-dependent technologies like heat pumps and solar thermal systems, or by estimating the effect of differences in industrial structure on heating demand (via a country comparison).

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3 A Review of the Emission Reduction Potential of Fuel Switch towards Biomass and Electricity in European Basic Materials Industry until 2030[31]

Abstract

In 2015, industrial sector installations included in the European emission trading system (EU ETS) emitted 574 Mt CO_2-equivalent Greenhouse gas (GHG) emissions. Among them are production of clinker, lime and ammonia, blast furnace operations, refineries and others. The emission intensity of these installations is closely tied to the fuel type used. Global warming scenarios of 1.5°C recently presented by the IPCC require fast emission reduction in all sectors until 2030, followed by deep reductions, reaching carbon neutrality around 2050. In this paper, the technical potential to use biomass and electricity with existing or available technologies in important industrial processes is reviewed. The investigated industries account for 95% of the total verified emissions in the EU ETS industrial sector 2015 and 64% of total industrial emissions of the EU28. We find that 34% (185 Mt) of these emissions could be avoided from a technical perspective until 2030 with fuel switch measures towards biomass and electricity. This reduction is in line with 1.5°C global warming scenarios until 2030, but further effort is required beyond that. We also find that available options lack economic competitiveness under present conditions, e.g. due to high electricity prices. We conclude that, although considerable fast emission saving potential by switching to biomass and electricity are possible, deep decarbonisation in line with climate targets requires innovative production processes only available in the long term.

[31] This chapter has been published in Renewable & Sustainable Energy Reviews as *Rehfeldt, M.; Worrell, E.; Eichhammer, W.; Fleiter, T. (2020): A Review of the Emission Reduction Potential of Fuel Switch towards Biomass and Electricity in European Basic Materials Industry until 2030*.

List of abbreviations

BAT	Beat available technology
CCS	Carbon capture and storage
DRI	Direct reduced iron
EAF	Electric arc furnaces
EEA	European Environment Agency
EU	European Union
EU ETS	European Union Emission Trading System
EUTL	European Union Transaction Log
EU25	25 European Union member states
EU28	28 European Union member states
EUR	Euro
FBB	Fluidized bed-boilers
GHG	Greenhouse gas
HHV	Higher heating value
IPCC	Intergovernmental Panel on Climate Change
Mt CO_2-eq.	Million tonnes carbon-dioxide equivalents
PCI	Pulverized coal injection
tpd	Tonnes (metric ton) per day
TRL	Technology readiness level
thm	Tonnes (metric ton) hot metal
MWh	Megawatthours
TWh	Terawatthours
PWh	Petawatthours

3.1 Introduction

In 2015, about 574 Mt CO_2-eq. of industrial greenhouse gas (GHG) emissions were included in the European Union emission trading system (EU ETS) [1][32]. The most important sources are production of clinker, lime and ammonia (with significant process emissions), blast furnace operations (extensive use of coke and coal), refineries and the generation of steam in several processes. Emission reduction targets on European level require a reduction by at least 40% until 2030 and 80%-95% until 2050 (compared to 1990). The publication of the special report on the impacts of 1.5°C global warming by the IPCC [3] received increased attention. A central finding (C1) in this report is that 1.5°C-scenarios consistently include a GHG decrease of around 45% below 2010-levels by 2030. 2°C-scenarios still include up to 30% reduction until 2030. These targets, based on 1990, demand emission cuts of 55% (1.5°C) or 40% (2°C) until 2030[33]. This level of ambition means that all sectors need to contribute. From 1990 to 2016, the EU28 manufacturing industries reduced their emissions (energy- and process-related) by 38% [4]. A considerable shift from liquid and solid fuels to natural gas contributed to these reductions, especially in the non-energy intensive industries [5]. With the exception of non-ferrous metals and the paper industry, however, the energy-intensive industries (iron and steel, chemicals, non-metallic minerals) did not participate in this trend. Due to the strong emission reductions after 1990, the industrial sector would have to reduce by 35% compared to 2016[34], to achieve a 55% reduction compared to 1990. This further reduction still means going beyond natural gas and energy efficiency and increasing the speed of transformation considerably.

Several technologies have been discussed that could facilitate further fuel switch in energy-intensive industries, often based on biomass and electricity. The main goal is to overcome the barriers that hindered fuel switch in certain key processes with new technologies. Lechtenböhmer et al. [6] analysed the role of electrification for deep decarbonisation of energy intensive industries, including steel, cement, glass, lime, petrochemicals, chlorine and ammonia. The developed scenario results in an industrial electricity demand increased by 170% compared to today. Rootzén and Johnsson [7] explored the emission reduction potential for the iron and steel, cement, refinery industry and the power sector using a stock model of industrial installations. They included fuel switch options for several processes and concluded that deep decarbonisation up to 95% requires innovative technologies. Investigating the metrics of industrial activity in the United States, Aden [8] concluded that energy and material efficiency is not sufficient for climate stabilization, and additional fuel

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32 For the purpose of potential estimation, we refer to the *verified emissions* of the industry (excluding the energy sector and transportation) reported by the EEA [2] from the European ETS register EUTL, when we use the term ‘emissions’. This should not be confused with the total emissions of the industry, as the emission trading system excludes sectors.

33 Based on already achieved emission reductions between 1990 and 2010 of about 900 Mt CO_2-eq. [4].

34 Data on 2010 with the same scope and detail is not available. However, since 2010, the emission from energy use largely stagnated around 500 Mt CO_2-eq. after a strong decline in 2009 caused by the economic crisis. The same is true for process-related emissions (around 380 Mt CO_2-eq.) [4].

switching away from fossil fuels is necessary. Fleiter et al. [9] found that processes in the energy-intensive industry in Germany had a remaining energy efficiency potential of about 14% until 2035 and that additional measures include fuel switching. Deep decarbonisation in the iron and steel industry is often associated with hydrogen- and electricity-based direct reduction [10], [1] or carbon capture and storage (CCS) [11]; [12]; [13]. A decarbonized cement industry is linked to new cement types [6], [14], extensive clinker substitution and CCS [15]. Regarding the non-ferrous metal industry, González Palencia et al. [16] found that, while effective in GHG-emission reduction, fuel switching to electricity and low-carbon fuels increases system costs. For the basic chemical industry (e.g. ethylene, ammonia, methanol), new production routes based on hydrogen or biomass are discussed [17]. Similar scenarios have been developed by other authors, emphasizing renewable hydrogen and the mitigation of process emissions in cement production [18]; or carbon capture and storage (CCS) [11]; [7]. These breakthrough-technologies and concepts are still in a pilot or demonstration-phase and are not expected to have a significant impact on GHG-emissions before 2040 [19] though first plants are planned for 2030 [1]. Industry stakeholders involved in the ETS Innovation Fund for example expect projects at technology readiness level (TRL 7) to be market ready after 5-10 years [20]. All deep decarbonisation strategies via innovative and breakthrough-technologies additionally include incremental changes to existing processes. The increase of energy efficiency beyond the current best available technology (BAT), fuel switch to less emission-intensive energy carriers, increased recycling and change of consumption patterns are recognized as necessary elements [1]. Gerres et al. [21] reviewed both efficiency gains in existing processes (e.g. BAT plants) and innovative technologies in energy intensive industries until 2050. They also include biomass use as emission reduction measure, finding highest potentials in cement and ceramic productions. They conclude that the optimization of current production processes is not enough to reach 2050 emission targets. They acknowledge that many of the identified technologies still are in early research phases, with market readiness not expected before 2030. Approaching the topic from their transitional aspects, Wesseling et al. [22] categorized several innovative, low carbon technologies for energy intensive industries by their TRL. They identified substantial economic, organizational, structural and political barriers for radical process innovations and found that the technologies necessary to meet 2050 GHG targets are dominantly in early TRL-stages (3-5).

If industry is to contribute to necessary fast emission reductions, it cannot wait for innovative processes. Fuel switching opportunities in existing processes thus seem a viable short- to mid-term action, as they tend to require limited systemic adaptation, benefit from knowledge spill over in other sectors and often carry co-benefits. As Grubler et al. [23] point out, transition processes are accelerated by these characteristics, while they are slowed by high technology complexity, large market sizes and infrastructure needs; which are characteristics common to innovative processes. However, fuel-switching options should not create path dependencies which could impede future innovative processes from penetrating. The existing literature shows that fuel switch is recognized as an important tool for short to medium term emission reductions but that considerable uncertainties exist with regard to its potential and what challenges individual industrial processes face. A comprehensive review of short-medium term fuel switch measures in energy-intensive industries is not available, as previous publications either focus on individual processes or investigate long-term emission reduction options.

This paper focuses on the industrial subsectors iron and steel, cement, glass, refineries, basic chemicals and pulp and paper that are present in the EU ETS[35]. These subsectors are often recognized as energy-intensive and thus of great importance for climate action [24], [9]. Other sectors are not considered due to their comparably low GHG emissions. This paper reviews and summarizes the potentials for early emission reduction of industry via fuel switching by 2030, using technically available technologies. First, we review opportunities for CO_2-reduction potentials via fuel switching in existing industrial processes, based on peer-reviewed scientific articles, contributions to conferences, international grey literature and industry publications (e.g. of equipment manufacturers). Secondly, we estimate the total fuel switching potential for the basic-material industries in the scope of the EU ETS. We differentiate specialized emission sources in key industries, and cross-cutting sources including boilers and generic furnaces. We conclude with a discussion on the economic challenges of the identified fuel switching opportunities.

35 The most relevant industrial activities not included are production of primary aluminum (7 Mt), production of processing of non-ferrous metals (7 Mt), production of nitric acid (5 Mt) and production of soda ash or sodium bicarbonate (3 Mt) [2].

3.2 Methodology and Data

Classification of considered technologies

Several technologies used for process heat generation have limitations on the fuel type used. In Table 3.1, various types of furnaces used in industrial processes are presented. Those that do not have special fuel requirements are summarized as "furnaces", for example distributed fired heaters in refineries, pusher-type furnaces and walking-beam furnaces for reheating, several types of heat-treating furnaces (bell-type, box-type), melting furnaces in metallic industries (multi-deck-furnace, some shaft furnace types) and tunnel-furnaces for the burning of ceramics. Some of these furnaces feature indirect heating, but direct contact of product and combustion gases is also common. Similarly, we assume that steam boilers can be fired with a broad range of fuel types, often in a flexible way or even in parallel (i.e. multi-fuel burner). For many installations, fuel switching still includes modifications, especially to the burner itself and to fuel-related infrastructure (storage, distribution). Steam systems are typically used to supply low to medium temperature heat (assumed here: up to 500°C). Furnaces can generate process temperatures above 1000°C, though temperatures between 500°C and 1000°C are most common. These technologies are also referred to as cross-cutting [21].

Literature selection

We review process- and technology-focused literature from the energy-intensive manufacturing industries. We include peer-reviewed scientific articles, conference contributions, grey literature (publicly funded research reports and industry publications, e.g. of equipment manufacturers) to assess the current state of discussion. We consider fuel switch options that are plausibly expected to be available in relevant scale until 2030. This selection is justified with an uncertainty estimation, taking into account the available experience with the technology.

The literature review is approached from two directions: First, literature focused on contemporary production processes is searched for experience with fuel switch, identifying state of the art biomass and electricity use as well as known challenges and barriers. Secondly, emission reduction measures are reviewed based on literature dealing with alternative technologies, their deployment and potential estimates of biomass and electricity. The use of biomass and electricity in steam systems and furnaces includes very heterogeneous applications (e.g. different temperature levels, boiler and furnace designs and products). However, the generation part is relatively homogenous and they are not facing the specific technical limitations of special furnaces. These special furnaces (e.g. blast furnace, glass melting furnace, steam cracker) are subsequently described individually.

Data sources

Main data source for GHG emissions is the transaction log of the EU ETS (EUTL). The EU ETS covers CO_2 emissions (energy-related and from process emissions) in the energy-intensive industries, power and heat generation and commercial aviation but also N_2O emissions, e.g. from nitric or adipic acid. The group of energy-intensive industries is further differentiated in 24 main activities. We create groups of processes with comparable energy systems[36]. The activities used in this publication are presented in Table 3.1. They accounted for 95% of industry's emissions in the ETS in 2015 [2], 64% of the GHG emissions of the entire industry in the EU28 in 2015 (861 Mt, [4]), and 75% of the industry's final energy demand in the EU28[37]. Their sectors also accounted for approx. 50% of total production value of the manufacturing sector [26].

In 2015, natural gas, electricity and coal were the dominant energy carriers in the EU industry with 719 TWh (30%), 657 TWh (27%) and 391 TWh (16%), respectively. The share of electricity used for heating purposes is low and was estimated below 7% of the total energy used for heating [27]. Biomass and derived energy carriers made up 179 TWh (7.4%) in these subsectors, 80% of which in the paper industry. Subsectors with notable use of specific energy carriers include iron and steel (coal and coke), non-metallic mineral products[38] I (hard coal, petroleum coke, lignite, waste) and non-metallic mineral products II (natural gas) as well as pulp and paper (biomass). These consumption patterns can be traced back to the products and process technologies. Similar classifications and utilization of industrial activity has been proposed by Wiese and Baldini [28].

Data processing

The literature review identifies the most discussed measures in the respective energy intensive industries. The estimates on emission reduction potential are checked for consistency among multiple sources and applied to the affected emissions reported in 2015 (Table 3.1). Energy- and process related emissions are separated based, among others, on Fleiter et al. [9]. For example, the change of fuel in clinker production only reduces the energy-related emissions and the reduction potential only applies to the ~60% energy-related emissions.

For the purpose of emission reduction estimation, we assume biomass and electricity to be GHG-neutral. Any supply-side emissions are thus excluded. This assumption allows estimating emission reduction without the consideration of country-specific energy systems, for example electricity generation mix. When possible, the emission reduction potential of the identified fuel switch options is directly taken from the reviewed literature. Similar to Gerres et al. [21], if the reduction potential is given on an energy basis, we weight the data with the emission factors of the replaced energy

36 Largely, this equals the division-level in the statistical classification of economic activities in the European community [25]. However, some processes that share a division require further differentiation (e.g. clinker and glass production).

37 According to Eurostat energy balances [5], in 2015, the energy intensive industries in the EU28 (steel, chemicals and petrochemicals, non-ferrous metals, non-metallic minerals, food and paper) had a final energy demand of 2415 TWh; the entire industry sector had 3211 TWh. The EEA reports 567 Mt of emissions in the EU28 in the activities 21-44 and 99, of which the considered activities cover 547 Mt [2].

38 Non-metallic minerals I (clinker and lime production) and II (glass and ceramics) have been split to highlight their energy carriers preferences, which differ substantially from each other.

carriers to calculate emission savings. When measures address the same emissions, the overlap is calculated separately. No priority for individual measures is assumed. Finally, we combine the evaluated measures and deliver a comprehensive look at the emission reduction potential of fuel switch in the investigated processes. The authors acknowledge that due to these assumptions, only a rough estimate on the emission reduction potential can be given and that considerable uncertainties exist.

Table 3.1: Investigated EU ETS-activities, important heating technologies and energy carriers [9]) and their CO_2 emissions 2015 ([2])

Subsector[1]	**Main activity[2]**	**Main processes/ product**	**Main energy carrier**	**Main heating technologies**	**Emissions 2015[2] (Mt CO_2-eq.)**
Refineries	Refining of mineral oil	Distributed fired heaters	Oil, natural gas, derived gases	Furnaces	128
Iron and steel	Production of pig iron or steel	Primary route	Coal	Blast furnace, converter	115
		Secondary route	Electricity	Electric arc furnace	-
	Production of ferrous metals	Rolling	Derived gases, natural gas	Furnaces	12
		Other reshaping	Natural gas	Furnaces	
		Heat treatment	Natural gas, electricity	Furnaces	
	Production of coke	Coke	Coal	Coke oven	12
	Metal ore roasting or sintering	Sinter	Coal, derived gases	Sinter oven	3
Non-metallic minerals I	Production of cement clinker	Clinker	Diverse fossil	Rotary kiln	114
	Production of lime	Lime	Diverse fossil	Rotary kiln	31
Non-metallic minerals II	Manufacture of glass	Flat glass	Natural gas	Float glass furnace	18
		Container glass	Natural gas	Glass furnaces	
		Other glass	Natural gas	Glass furnaces	
	Manufacture of ceramics	Ceramics	Natural gas	Furnaces	16
Basic chemicals	Production of ammonia	Ammonia	Natural gas	Steam systems	32
	Production of synthesis gas	Synthesis gas	Natural gas	Steam reformer	
	Production of bulk chemicals	Ethylene	Naphtha, natural gas	Steam cracker	39
		Methanol	Natural gas	Steam systems	
Pulp and paper	Production of paper or cardboard	Paper	Natural gas, biomass	Steam systems	22
	Production of pulp	Pulp	Natural gas, biomass	Steam systems	5
Sum					**547**

1: Eurostat definition [5]
2: ETS definition [2]

3.3 Review of Technologies for Fuel Switching

3.3.1 Biomass use in steam systems and furnaces

The use of biomass for steam generation is particularly well researched for co-firing in coal-fired power plants. Biomass co-firing is seen as an important option to reduce CO_2 and SO_2 emissions, with sulphur content mass fraction as low as 0.1, compared to 1-3 in coal. The effect of biomass combustion on NO_x emissions is ambiguous, ranging from increased [29] to decreased [30]. The optimization of burner operation, furnace design [31] and type of biomass are key factors. Co-combustion with other fuels like natural gas and oil may also offer operational advantages [29]. However, co-firing shares are restricted to relative low percentages (5-10%, [32]). Although factors affecting injection rates are always plant-or site-specific, the general issues encountered in power plant steam generation are also relevant for steam generation and many furnace types in industrial processes. Three main challenges can be distinguished: boiler/ furnace operation, fuel handling and fuel properties.

Boiler/ furnace operation (ash deposition)

Depending on biomass type, the ash composition can vary considerably [30] compared to coal. Biomass has higher concentrations of alkali metal and chlorine, which increases the potential for fouling and slagging [32], [33]. When fouling and slagging occur, boiler tubes are coated with melted ash. Ash deposition hinders heat transfer and reduces the overall efficiency of the boiler, while increased corrosion (twice as high with 22% co-firing compared to coal alone [34]), shortens maintenance intervals or damages the boiler. Boiler design and operation may decrease fouling and slagging-risks. Especially pulverized fuel combustion boilers are vulnerable, while fluidized bed boilers (FBB) can mitigate the effect [35]. Therefore industries that typically use biomass-based fuels, e.g. wood-processing, pulp and paper industries, apply FBB-technology [36]. Obernberger [31] presents an overview of furnaces suitable for biomass combustion and fuel properties, including guiding ranges of elements in biomass fuels for unproblematic furnace operations.

Fuel handling/logistics

Due to its higher moisture content (ranging from 25% to 50% if untreated [30]), biomass has a much lower density and energy content than most currently used fuels. The required space for fuel storage, delivery and processing is therefore larger. Compared to coal, a factor of 10 can apply [32], [37]. Therefore, high biomass-shares are harder to realize in existing plants. The moisture content also limits storage strategies, as the fuel can be biologically active and decay, releasing gases and heat [30]. Thermochemical and physical treatment of biomass can therefore be necessary in installations with high energy demand. Several treatment processes are available, e.g. torrefaction, drying, pelletizing [38], [32], gasification and pyrolysis [39]. These upgrade the biomass to a more versatile fuel by reducing its water content, increasing density and heating value. For example, torrefied wood pellets may achieve a bulk density of around 15 GJ/m^3 [38] (coal: 45 GJ/m^3).

Biomass standards/ biomass properties

The properties of biomass can vary substantially. The higher heating value (HHV) can range from 11 MJ/kg to 22 MJ/kg [34] (coal: around 29 MJ/kg) and is highly influenced by the moisture content. The ash fusion temperature can be similar to coal (for wood) or substantially lower (straw). The volatile matter content is usually higher than in coal and shows a certain range [30]. Especially in high-temperature applications, the heating value may limit or hinder the use of biomass [40]. A useful differentiation for the heating value is by the main types woody and herbaceous plants [37], distinguishing by plant type, i.e. high (wood) and low (herbaceous). Despite these categories, biomass remains a very heterogeneous fuel group. Therefore, finding the suitable type of biomass in sufficient quantities is often a barrier [35]. The need for standardization of biomass fuels and their characterization is expressed [32], [33]. Fernando [30] shows that ash deposition rates vary substantially between for example wood (below 0.1 g/kg fuel, lower than coal) and straw (above 10 g/kg fuel), which may limit co-firing shares. Thus, a well-defined blend of biomass types and/or other fuels may mitigate some of the shortcomings of any individual type of biomass.

Table 3.2 summarizes the factors affecting biomass use in steam generation. While in general, technological solutions for the described challenges exist [31]; their application in the market is tied to the replacement of old technologies, the installation of new plants or modification of existing ones. According to [30], the use of biomass in existing coal-fired boilers is limited to 10%. Slagging and fouling becomes an issue above 10% cofiring-rate. The use of upgraded biomass (i.e. drying, removal of corrosive and slagging substances) could increase the share further, eliminating or reducing concerns about bulk density and to some degree slagging and fouling. The definition of mixtures for specific applications and installations could potentially increase biomass use further. Some consumers, e.g. clinker producers, generally employ quality-assurance systems regarding raw materials and fuels [41]. However others often lack sufficient expertise or motivation to change their fuel composition, e.g. when energy supply is not a core process. Finally, the use of steam systems and furnaces specifically designed to use biomass (e.g. fluidized bed or stoker designs) could mitigate limitations [29].

Table 3.2: Properties and solution of biomass-use in steam boilers and furnaces

Dimension	Property	Barriers	Solution	Technical feasibility
Energetic	water content	energy density, stability of combustion, storage	Thermochemical and physical treatment ('upgraded biomass')	mid-term
	heating value	energy density		
		flame temperature, air demand, flue gas volume		
Chemical	elemental composition	ash melting and deposition (fouling and slagging)	Mixture of biomass types and other fuels ('defined mixtures')	mid-term
			Furnace and boiler design	long-term
	flue gas composition	flue gas treatment systems, waste heat usage	Mixture of biomass types and other fuels ('defined mixtures')	mid-term
	share of volatiles	stability of combustion		
Physical	bulk density	transport, process and storage	Thermochemical and physical treatment ('upgraded biomass')	mid-term
	particle size	storage, burner operation		
	hydrophilic/ hydrophobic behaviour	storage		

For the estimation of emission mitigation potential, we assume a currently possible biomass use of 10% (short-term measure), and a long-term technical potential of 100%. This assumes that the mentioned issues (heating value and water content, elemental composition and volatile shares) are sufficiently addressed. Until 2030, however, stock turnover of steam systems and furnaces limits diffusion. Thus we assume a medium-term (until 2030) potential of 50%, combining modernization and new installations[39].

3.3.2 Electric boilers and furnaces

With the prospect of a decarbonized electricity generation, electric boilers and furnaces show potential to reduce GHG emissions from process heating as well. While the technology itself is proven and available on the market [42], economic challenges limit its use to niche applications that benefit of the characteristics of the technologies, e.g. safety, high temperatures, possibility of inert atmospheres, temporal and spatial temperature distribution and high energy density. Still, a variety of electro-thermal technologies and principles exist. From a technical point of view, close to all heating applications could be supplied electrically. Several examples are discussed by Rudolph and Schaefer [43], including electrolytic processing of metals, electric glass furnaces, paper drying, electric arc furnaces in steel production and steam/hot water supply. The processing of sensitive material that could be contaminated by fuel combustion; furnaces with high temperature (e.g. electric arc furnace) or important temperature profiles (glass furnace) are first candidates for electric process heating. In current installations, differences in capacity of a factor three (e.g. glass furnaces) to ten

39 This assumes a common lifetime of 15-25 years, not expecting early replacement. Additionally, this assumes that all existing stock installations are exchanged equally and no energy carrier-related preferences exist. For a closer look, the stock exchange should be modeled.

compared to common fuel-fired applications exist. Due to substantially reduced flue-gas losses, electricity-based furnaces have in general a higher energy efficiency [44].

While some sources stress several advantages of electric steam generation over fuel-driven boilers, e.g. lower investment costs and the lack of start-up costs or ramping constraints [45] and no local air pollution, economics make them currently less attractive. Han et al. [46] calculate a factor 3 higher operating costs compared to a gas-fired boiler, despite relatively high gas prices used in the study. Yilmaz et al. [47] calculated the levelized costs of heat of an electric boiler compared to a gas boiler, finding that an electricity price of 40 EUR/MWh would yield parity. The 2015 EU28 average industrial electricity price of 114 EUR/MWh thus suggests a limited economic potential for electric boilers[40]. Therefore, electric boilers are mainly considered flexibility options for an electricity system with high shares of intermittent renewable generation [49],[46,50]; feeding in a district heating system or supporting industrial heat demand [47]. In this application, they would make use of negative residual load and corresponding near-zero or negative electricity prices. This business model entails short operation intervals and is not suitable to supply baseload steam demand for industrial processes. Despite these general and process-specific limitations, Wiese and Baldini [28] estimate an achievable electrification share of 88% and 25% for low- and high-temperature process heat, respectively.

We summarize that all applications classified as “steam systems” or “furnaces” in Table 3.1 could be operated with electric systems. The same assumptions on stock turnover and modernization as for biomass (50% until 2030) apply. An overview of the challenges is presented in Table 3.3.

Table 3.3: Properties and solution of electric boilers and furnaces

Dimension	Property	Barriers	Solution	Technical feasibility
Technical	Capacity	decreased energy efficiency decreased economic efficiency	upscaling	mid-term
Economical	Electricity price	failing in competition against fuel-based technologies	lower electricity price	long-term
			higher fuel prices	short-term
Physical	Emission intensity of electricity generation	lowered ecologic benefit	increased renewable share	mid-term

3.3.3 Review of individual processes

Refineries

Refineries process crude oil into a variety of gases, fluids and solid fossil fuels and petrochemical products. They are complex systems with diverse processes, requiring electricity, steam and direct heating, and a variety of fuels with differing heating values are applied. Self-produced or derived gases from the production process supply a substantial share of the fuel in refineries. Under current economic conditions, it is more attractive to use them as fuel than as, e.g. feedstock in the chemical

40 During 2015, the electricity prices for non-household consumers (excluding recoverable taxes) varied between 81 EUR/MWh (demand >70 GWh) and 146 EUR/MWh (demand <20MWh), depending on the consumption band [48].

industry. In the period 1990-2015, approximately 45% of the energy input of the EU refining industry was supplied by derived gases [5], with a low of 10% in Poland (1998) and highs of 70% in Spain (2011). Other energy carriers include fuel oil, natural gas (25% of EU28 energy consumption in 2015 [5]) as well as petroleum coke and several minor fuels (~5%). Fired heaters make up for 30-60% of emissions in a refinery and experiments have been carried out to replace the usual refinery fuels and methane with hydrogen [51]. Limited impact on performance was found, suggesting that no specific fuel composition is required. While from a technical perspective, all process heat in refineries could be supplied using biomass- or electricity-based supply, replacing derived gases and petroleum coke would only shift emissions, since they are a by-product.

We assume that immediate fuel-switch potentials are limited to the replacement of purchased fuels (i.e. natural gas) by biomass or electricity. As purchased fuels account for about 30% of refineries energy demand, this would equal a 33% CO_2 emission reduction (considering the emission intensity of the replaced fuel mix in the EU28 in 2015).

Iron production

Blast furnaces are highly specialized shaft-furnaces and the most energy and emission intensive process step in ironmaking. Blast furnaces rely on fossil fuels, particularly coke and (injected) coal. The former is essential for mechanical support and a free gas flow[41], and limits a shift to other energy carriers. The minimum use of coke is driven by the blast furnace geometry and operation, and can only be estimated on today's best practices [52]. The average coke consumption in blast furnace operations in Germany has decreased considerably from over 1000 kg/t_{hm} in 1950 to 400 kg/t_{hm} in 1990 [53], but only slightly since to about 360 kg/t_{hm} in 2010 [54]. Otto et al. [55] report the total energy input in an average blast furnace with 15.95 GJ/t_{hm}, of which 4.67 GJ (143 kg) are supplied by coal (pulverized coal injection, PCI) and small quantities of natural gas and 10.3 GJ (359 kg) by coke. A value of at least 300 kg/t_{hm} of coke and a total of 500 kg/t_{hm} of reduction agents and fuels is a reasonable estimate for modern blast furnaces[42] [57].

Fuel switching options in a blast furnace include the use of biomass-based fuels in coke making and the injection as auxiliary fuel. The former option invokes the discussed requirements on coke properties. The latter does not and is thus more promising [58]. Both options need to be distinguished from pure charcoal-based ironmaking, which is active in Brazil, but given little credit for global deployment, due to the limited capacity of the furnaces[43]. (Suopajärvi et al. [56] show that a coke rate

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41 Additionally, they provide energy and carbon as reducing agent, which also lowers the melting point of the iron to a eutectic minimum.

42 Coke use of around 200 kg/t_{hm} have been reported, but are related to the not commercially available technology top gas recycling [56].

43 The largest charcoal blast furnaces (CBF) are reported to have a capacity of 1200 t_{hm}/d [59], while the largest conventional blast furnaces can reach 12.000 t_{hm}/d.

as low as 260 kg/t_{hm} is plausible, incurring additional side benefits to the process, e.g. higher metal quality and productivity. Regarding biomass injection in the blast furnace, Suopajärvi et al. [57] conclude that charcoal shows best promise to replace pulverized coal. Additionally, Wang et al. [58] find that the replacement of PCI with charcoal also lowers lime consumption by around 20% and overall energy demand due to increased latent heat in the top gas. However, several adjustment to blast furnace operations are needed to use the potential. Though experience is limited to mathematical models, lab-scale experiments or small blast furnaces in Brazil [59], several studies reviewed by Suopajärvi et al. [57] show a potential for emission reduction by biomass injection of 20-40%, up to a full replacement of injected coal. The partial use of biomass in coke production (bio-coke) is also discussed. Ng et al. [60] found that adding biomass as high as 5% to coke production lowers not only the overall GHG emissions, but also yields additional benefits to the BF process (e.g. better carbon utilization). They acknowledge that the mechanical strength of the resulting coke can be lower than that of regular coke at higher rates and thus the applicable share of biomass is indeed limited. Suopajärvi et al. [57] report a range of achievable coke-substitution (5% to 20%), depending on the type of biomass.

We include the individual measures of biomass in coke making (up to 10% of coke, reducing emissions by 6%) and substitution of pulverized coal with biomass in the blast furnace (emission reduction around 30%).

Coke oven

Coke ovens remove volatile components from coal to form coke. They use these volatile components and on-site process gases as fuel, in turn exporting cove-oven gas. Therefore, little fuel switch possibilities exist. However, a reduction in coke use lowers coking emissions proportionally. Emission savings due to biomass addition to coke is assigned to the blast furnace, but could just as well be assigned to coke ovens, due to site-internal use of process gases.

Sinter oven

Similar to coke ovens, sinter plant emissions would be reduced by a shift towards more EAF-based steel production. With coke breeze being the dominant energy carrier in sinter plants [54], fuel switching towards biomass and electricity can be effective. According to [57] up to 40% of the coke breeze could be replaced with biomass, the resulting emission reductions can be estimated to 1 Mt CO_2-eq. However, experiences are restricted to lab-scale sinter tests. The measure is therefore not considered further.

Electric arc furnace (steel production)

EAFs are mainly used in steelmaking from scrap; they can replace high quality steel production if part of the scrap is substituted by direct reduced iron (DRI). DRI is manufactured in a gas or coal-based process. EAFs mainly use electricity, with little addition of injection fuels, and thus have the potential to operate nearly GHG-neutral. The use of DRI increases the power demand of the EAF.

Steel production based on scrap/EAF is less emission intensive than the blast furnace route. However, high quality scrap availability may limit the achievable production rate. Of major concern are the dilution of alloying elements and copper contamination in contemporary scrap [61]. Depending on macro-economic and technology assumptions, certain shares of scrap-based steel on the total production seem plausible. Based on Herbst [62], an ambitious estimate on demand development for the EU28 yields an EAF potential of 50% in 2030 (2015: 39%). This neither considers direct reduced iron as potential feedstock nor advanced steel recycling. Both technologies are unsure to be available in the near future.

We assume that a scrap-based EAF share of 50% on total steel production is achievable until 2030 [62]. We use average emission intensities based on Arens et al. [10] of 1.82 tCO_2/t and 0.11 tCO_2/t for the blast furnace and scrap/EAF route (excluding electricity), respectively. The actual impact of this production shift depends on the other measures influencing blast furnace emission intensity. Steel production in this secondary route involves a process switch and thus more effort than many fuel switch options. It is still included in this analysis because the technology is competitive today and has comparatively low capital costs, enabling faster diffusion.

Rotary kiln (production of clinker)

Rotary kilns use a variety of fuels and are often equipped with multi-channel burners for simultaneous burning of solid, liquid and gaseous fossil fuels and waste [41], [63]. In pre-calciner rotary kilns, fuel can also be injected in the pre-calciner, where lower reaction temperatures allow for a broader selection of fuels, especially with lower heating values. According to Shahin et al. [64], the rotary kiln is the most used type of kiln in the non-metallic minerals industries. In Germany, over 98% of clinker is produced in rotary kilns. The share of solid fossil fuels (pet-coke, coal) used in the non-metallic minerals in the EU28 is quite stable over the past decades at about 30%. Renewables and waste shares increased from 1% to 4.8% and 0.2% to 7.7%, respectively, during 1990 and 2016 [5], mainly replacing heavy fuel oil. These waste fuels are non-renewables such as tyres, plastics or industrial waste and thus do not reduce the emission intensity of clinker production considerably.

GHG mitigation options include an increased use of biomass in the alternative fuel/refuse-derived fuel fraction and replacement of primary fossil fuels (lignite, hard coal, coke, fuel oil). Secondary fuel shares of 70-80% have been observed [65], [66] in individual plants. Assuming upgraded biomass with suitable heating value was available, it could theoretically supply the entire energy input in rotary kilns. Since the raw material is in direct contact with the flue gas, the fuel composition can influence clinker quality, which means that especially the mineral components of biomass need to be controlled and considered for the raw material mix [67]. Replacing the energy input with GHG-neutral fuels could reduce the emissions from clinker production by approximately 40% to 0.53 $tCO_2/t_{Clinker}$ [68]. We assume that fossil and waste-derived fuel can be substituted completely with biomass-based fuels, reducing energy-related emissions (40% of total). Electric heating is not considered as an option in the near future. Examples include the theoretical possibility to apply indirect-heated rotary kilns [69] that are used in special applications. Those are, however, not capable to deliver the required capacities and currently not considered in the industry.

Shaft kiln (production of lime)

Similar to cement clinker, lime is produced by the calcination of limestone, resulting in 0.75 tCO_2/t_{Lime} process-related emissions. While rotary kilns can be used, the more energy efficient shaft furnaces dominate in Europe. More than 50% of the global lime production is used as metallurgical lime in the steel and non-ferrous metals industry, for example to remove impurities, especially sulphur [70]. Therefore, the sulphur entry during lime production must be controlled, which limits fuel use to low-sulphur types.

Most types of biomass contain much less sulphur than coal. Low-sulphur coal is defined as a mass fraction of sulphur < 1 sulphur, while most biomasses show 0.1-0.2 [34], [37]. Indeed, pulp mills in Sweden fuel their captive lime production with biomass for decades, with biomass fuel rates up to 95% [71]. We include the measure to substitute fossil fuel completely with biomass-based fuels, mitigating energy-related emissions (35% of total).

Glass melting (flat & container)

Glass is produced by melting the raw material sand, soda ash, limestone (and others) in a furnace. It is usually heated with natural gas burners (79% in 2007 in EU25 [72] and supported with electricity. Small electric furnaces are already used for specialty glass products. Emissions occur due to energy use (0.57 tCO_2/t) and process emissions (0.12 tCO_2/t) (process-weighted EU28 average according to Schmitz et al. [72].

All-electric melting furnaces are theoretically available for most glass types and discussed in the industry as possible alternative to natural gas furnaces [73], but more common in smaller batch furnaces used for container glass and technical glass. With the electricity price and lower capacity being the main disadvantage compared to fuel-fired furnaces, their actual use is severely limited [72]. While common fuel-fired furnaces reach capacities of 400-700 tpd (tonnes per day) [74], all-electric furnaces of 175 tpd are considered large, with an assumed practical maximum of 300 tpd. In addition to their potentially GHG-neutral heat supply, all-electric furnaces can be more efficient, with roughly 80% fuel efficiency (fuel-fired around 50% at similar sizes) or 800 kWh/tonne.

Here we assume that all-electric furnaces can be scaled up sufficiently to deliver the required capacity. Therefore, the energy related emissions (80% of total) could be theoretically mitigated[44]. This could be applied to all major glass products, with the possible exception of some glass types with foaming tendency due to feedstock composition [75]. As all-electric glass furnaces requires new installations

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44 This is on the upper limit of possible emission reductions summarized by Gerres et al. [21].

or extensive revisions in existing plants, we assume (similar to steam systems) that 50% of the potential can be realized until 2030.

Steam reformer (synthesis gas production)

Steam reformer produce synthesis gas (H_2 and CO_2) out of fossil fuels (e.g. methane). The two most important applications for the synthesis gas are ammonia and methanol production. Steam reformer use both steam (mixed with the carbon-carrying feedstock) and furnaces, further heating the gas mixture, to create the required reaction environment. The energy input can be considered to originate from the furnace, since the steam is generated with furnace excess heat. The production of ammonia and methanol require temperatures between 400 and 500°C, and 200 to 300°C, respectively. Steam may be generated with excess heat from gas cooling [9].

CO_2-Emission reductions focus on the generation of synthesis gas: Hydrogen production via electrolysis seems to be a natural step and ammonia could be an important part of a hydrogen-based energy system [76]. Considering biomass as feedstock, the concept of a bio-refinery [77] would present an integrated approach for the production of several bulk chemicals. Both technologies are not on the market, though, and unlikely to be available in impactful capacities until 2030. Ethanol-based hydrogen production via steam reforming is discussed, but catalysts are still being researched [78], [79]. Direct electric heating has been discussed with regard to efficiency gains, maintenance reduction and methane use [80]. While the concept has been demonstrated, the authors also mention several challenges to widespread implementation. If applied, it could replace the natural gas used as fuel (20 - 25% [80], [81]. Replacing natural gas with upgraded biogas as feedstock and fuel is seen as technically viable for almost all current reforming processes [82]. Solar-heated approaches are also discussed [83]. Here, we assume that electro-thermal reforming is in principle possible in a retrofitted steam reformer, eliminating the emissions caused by the use of natural gas as fuel. This equals an emission mitigation potential of 20-25%. We assume that limited use of bio-based syngas, replacing the natural gas used as feedstock (25%), can also be introduced until 2030.

Steam cracker (ethylene and other chemical products)

Steam cracker split hydrocarbons (mostly naphtha in Europe) into shorter molecules that are used in several chemical processes (e.g. ethylene). Similar to steam reforming, heat is supplied by both steam (mixed with the feedstock stream) and furnaces (used to further heat the mixed stream). However, superheated steam is generated in the furnace and recycled as saturated steam [84]. Heat supply originates from the furnace. Natural gas or fuel oil are used in cracking furnaces, but due to NOx-emission, oil use declined strongly [84], a trend which can be observed in the entire chemical industry [5]. Energy-related emissions from furnaces and steam systems account for 65% of the 1.5-2.1 $tCO_2/t_{Ethylene}$ [85].

Options to reduce GHG emissions focus on the use of sustainable feedstock alternatives to the fossil naphtha. Revolutionary concepts include the use of hydrogen or the complete replacement of the platform-chemical ethylene [76]. Other approaches aim to replace fossil-based feedstock with bio-based counterparts, essentially generating sustainable ethylene and moving from petro- to bio-chemistry. The energy-intensive cracking process would become obsolete, as e.g. ethanol requires only dehydration to become ethylene, with a comparably little energy demand of about 1.68 GJ/t [17] (naphtha-based ethylene: 36GJ/t [9]. For all these concepts, the availability of biomass or cheap electricity for hydrogen production is critical. Less invasive measures include the mere replacement of fossil fuel use for heating purposes with biomass or electricity. These approaches would have a smaller impact on the down-stream value chain since ethylene (and C3, C4 co-products) could potentially be supplied as usual. While this would allow the majority of installations in a steam cracker to remain in existence, it is debatable what effects changed fuel sources could have on the steam cracker system. Different bulk densities, burner design and the use of waste streams (in some furnace designs up to 70% of energy use [84] from the cracking process may pose a challenge to efficient operations. The product itself would still carry a fossil GHG load and cracking residues (ethane, fuel oil, hydrogen, methane, and propane) would require another, preferable long-term, sink. We assume that no currently feasible fuel switching opportunities exist for steam crackers, because practical sinks for the cracking residues are missing.

Summary

Both the applicability and availability of the proposed fuel switching measures are subject to uncertainty. We estimate the readiness of the measures by the amount of practical experiences documented in the reviewed literature (Table 3.4). We use the technology readiness level (TRL) scale as defined by Horizon 2020 and used in [1]. The categories range from widespread experience and deployment (TRL 8-9) over transferable technology and small-scale demonstrations (6-7) to model calculations and experiments (5). TRLs lower than that are not considered available until 2030 and thus excluded.

Table 3.4: Summary of investigated measures

Technology/Process	Measure	Statement from source	TRL[1]	Emission reduction potential compared to 2015[2]	Comment[3]	Source
Refinery	Replacement of natural gas	Specific: burner retrofit experiments; General: available technology (furnaces)	8	33%	Assumed exchange of purchased fuel only	[51]
Iron production	Replacement of PCI with biomass	Blast furnace models, small blast furnaces	7	30%	-	[58], [57], [59]
	Biomass in coke production	Pilot-scale coke oven	6	6%	-	[57], [60]
Steel production	Shift to secondary route (EAF)	Established production route	9	11% (50% EAF share)	Scrap quality is a challenge for high shares (39% 2015)	[62], [61]
Clinker production	Substitution of fossil fuels with biomass in rotary furnaces	Documented fuel-flexibility	8	39% (all energy-related)	Treatment and standardization of biomass necessary	[68], [65]
Lime production	Substitution of fossil fuels with biomass in shaft furnaces	Industrial experience in paper industry (captive lime production)	8	35% (all energy-related)	Lower sulphur content than coal	[34], [71]
Glass production	All-electric furnaces	Available technology, economically challenged	8	40%	Upscaling required; 50% diffusion until 2030	[73], [72]
Steam reformer	Electro-thermal reforming	Specific: experiments; General: available technology (furnaces)	6	25% (all energy-related)	Solar heating also discussed	[80], [83], [43]
	Biomass gasification for fuel supply	Proven technology for natural gas replacement	8	25% (all energy-related)	-	[82]
Steam cracker	None	-	-	-	By-products require a sink	[84]
Steam generation and furnaces	Electricity and biomass use	Available technology, economically challenged	9	50%	Exchange of old boilers; 50% diffusion until 2030	[42], [31], [43]

1: TRLs based on author's judgement of reviewed literature.

2: Derived from literature review. Potentials are assumed reachable until 2030 with determined but realistic action in existing plants and with technically available technology. The potentials may not be economic under current frame conditions but could become so (near-economic potentials) or may also be hampered by non-economic barriers. Restrictions may be mentioned in column ‘Comments’.

3: Relevant restrictions, side-benefits and challenges to deployment (already considered in emission reduction potential).

3.4 Results

We calculate the emission reduction potential of the measures identified in the previous sections with respect to the emissions in 2015 (Table 3.1). That is, we neglect efficiency improvement potentials [86], [87] and activity changes, which would likely occur until 2030. The identified measures are categorized as biomass- and electricity-use (Figure 3.1 by technology, Figure 3.2 by fuel switch option). These individual measures overlap to some degree, i.e. both biomass and electricity could be used in some applications.

Biomass- and electricity-based team systems and furnaces contribute 28 Mt CO_2-eq. and the replacement of natural gas used as fuel in steam reforming with biomass or electricity each 8 Mt CO_2-eq. Biomass use in lime and clinker production can reduce emissions by 57 Mt CO_2-eq. and all-electric furnaces in glass melting 7 Mt CO_2-eq. The discussed measures in the iron and steel industry (shift to EAF, biomass injection in blast furnaces and biomass addition to coke) contribute 35 Mt CO_2-eq. and the replacement of purchased fuel in refineries with biomass or electricity 42 Mt CO_2-eq. All measures combined, 34% of the investigated emissions in 2015 could be mitigated (185 Mt CO_2-eq. out of 547 Mt CO_2-eq.). Biomass measures individually could save 162 Mt CO_2-eq. (69 Mt CO_2-eq.without overlap), and electricity measures individually 115 Mt CO_2-eq. (22 Mt CO_2-eq.without overlap). The emissions addressable by both biomass- and electricity-based fuel switch amount to 93 Mt CO_2-eq.

With the considered short/medium-term options, emissions remain that cannot be mitigated until 2030 (87 Mt CO_2-eq., Table 3.5). These emissions could potentially be mitigated in the long-term (*Beyond 2030*) or in aggressive fuel switch scenarios (e.g. faster steam system and glass furnace exchange before the end of their lifetime and availability of large quantities of biomass- or hydrogen-based feedstock). These emissions include 28 Mt CO_2-eq. in steam systems, 16 Mt CO_2-eq.in steam reforming, 5 Mt CO_2-eq.in glass production and 39 Mt CO_2-eq. in steam cracker. The presented reduction potentials also reveal emissions (*Process switch*) that cannot be addressed with the discussed inter-fuel substitution measures (275 Mt CO_2-eq.). They consist of fuel use in mineral oil refining (86 Mt CO_2-eq.), coke and sinter use and preparation in iron and steel (94 Mt CO_2-eq.) and process emissions in clinker, lime (89 Mt CO_2-eq.) and glass and ceramic production (6 Mt CO_2-eq.). These emissions could be mitigated with radical process changes (e.g. change of raw material) but not within the existing processes.

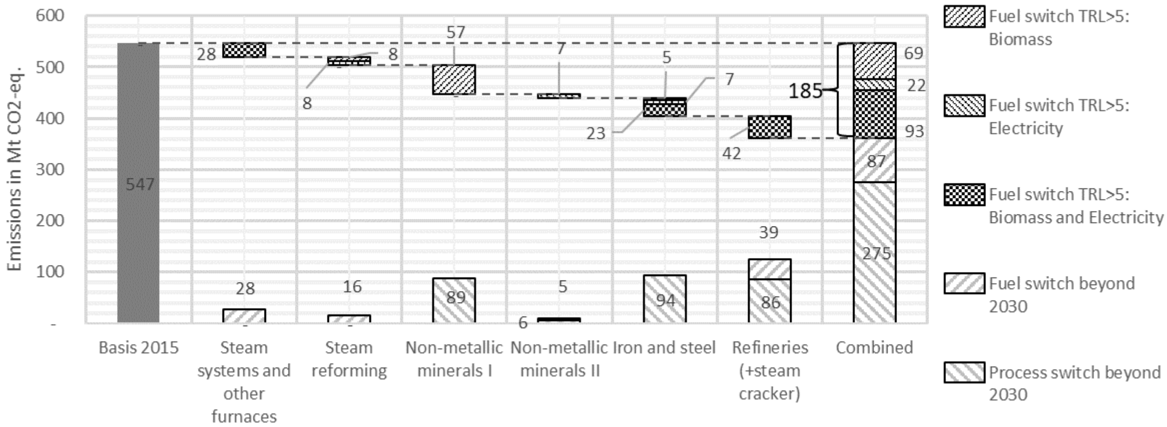

Figure 3.1: Estimated GHG-emission reduction potential (by technology), (potential for emission reduction in existing industrial processes using the selected fuel switch options; selected measures are technically available and deemed plausible to be implemented on meaningful scales until 2030; 'Beyond 2030' emissions are avoidable only after 2030 by fuel switching measures; 'Process switch' emissions cannot be mitigated with fuel switch measures but require radical process changes)

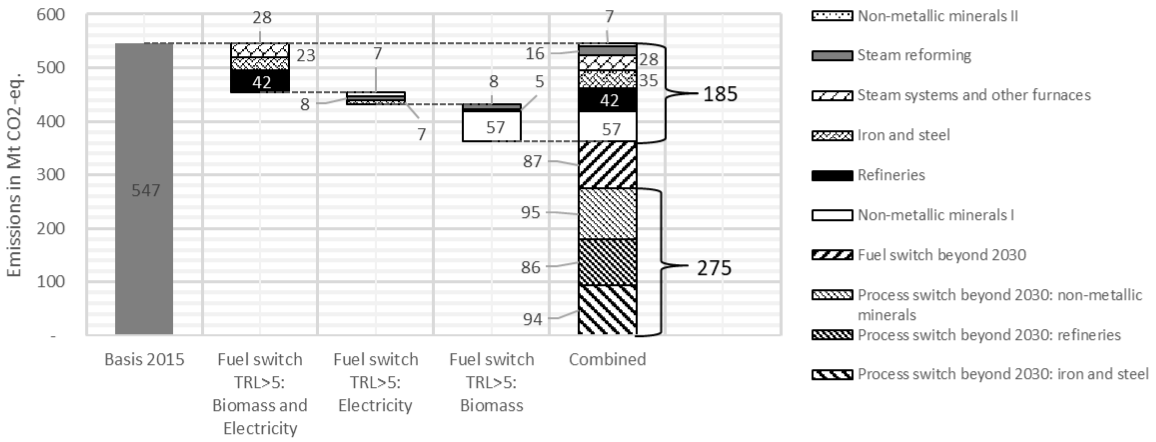

Figure 3.2: Estimated GHG-emission reduction potential II (by fuel switching option), (potential for emission reduction in existing industrial processes using the selected fuel switch options; selected measures are technically available and deemed plausible to be implemented on meaningful scales until 2030; 'Fuel switch beyond 2030' emissions are avoidable only after 2030 by fuel switching measures; 'Process switch beyond 2030' emissions cannot be mitigated with fuel switch measures but require radical process changes still in development)

Table 3.5: Biomass and electricity emission saving potential[45] and residual emissions

Subsector	Main activity (EU ETS)	Products	Main energy carrier	Heating technologies	Emissions 2015	Reduction potential biomass[1]	Reduction potential electricity[1]	Reduction potential combined[2]	Beyond 2030[4]	Process switch[3]	Share on remaining
					Mt CO_2-eq.						
Refineries	**Refining of mineral oil**	Mineral oil products	Oil	Distributed furnaces	128	42	42	42	-	86	24%
Iron and steel	**Production of pig iron or steel**	Oxygen steelmaking	Coal	Blast furnace, converter	115	30	31	37	7	71	22%
		Electric steelmaking	Electricity	Electric arc furnace	-	-	-	-	-	-	0%
	Production of ferrous metals	Rolling	Coal, natural gas	Furnaces	12	6	6	6	6	-	2%
		Other reshaping	Natural gas	Furnaces						-	
		Heat treatment	Natural gas ,electricity	Furnaces						-	
	Production of coke	Coke	Coal	Coke oven	12	-	-	-	12	-	3%
	Metal ore roasting or sintering	Sinter	Coal, derived gases	Sinter oven	3	1	-	1	2	-	0%
Non-metallic minerals I	**Production of cement clinker**	Clinker	Diverse fossil	Rotary kiln	114	45	-	45	-	70	19%
	Production of lime	Lime	Diverse fossil	Shaft kiln	31	12	-	12	-	19	5%
Non-metallic minerals II	**Manufacture of glass**	Flat glass	Natural gas	Float glass furnace	18	-	7	7	7	2	3%
		Container glass	Natural gas	Melting furnace						1	
		Other glass	Natural gas	Melting furnace						0	
	Manufacture of ceramics	Ceramics	Natural gas	Furnaces	16	8	8	8	5	3	2%
Basic chemicals	**Production of ammonia**	Ammonia	Natural gas	Steam systems	32	8	8	16	16	-	4%
	Production of synthesis gas	Synthesis gas	Natural gas	Steam reformer						-	
	Production of bulk chemicals	Ethylene	Naphtha, natural gas	Steam cracker	39	-	-	-	39	-	11%
		Methanol	Natural gas	Steam systems						-	
Pulp and paper	**Production of paper or cardboard**	Paper, cardboard	Natural gas, biomass	Steam systems	22	11	11	11	11	-	3%
	Production of pulp	Pulp	Natural gas, biomass	Steam systems	5	3	3	3	3	-	1%
Sum					**547**	**165**	**115**	**187**	**107**	**251**	**100%**

1: Only individual measures, ignoring overlap. Electricity and biomass potential cannot be summed up.
2: Excluding overlap of electricity and biomass measures
3: Emissions that cannot be avoided by fuel switch measures in existing processes (process emissions, required energy carriers)
4: Emissions that are assumed not to be avoidable until 2030 e.g. due to stock inertia (but may be later)

45 Definition of potentials (see also Figure 3.1): Potential for emission reduction in existing industrial processes using the selected fuel switch options. The selected measures are available on the market and deemed plausible to be implemented on meaningful scales until 2030.

3.5 Discussion

While the main part of the analysis focused on the technical feasibility, we discuss the role of additional factors below. Among these are the cost-competitiveness of electricity, the sustainability of biomass and estimations on their respective potential.

Challenges to the identified fuel switch options

From an economic perspective, the discussed technologies are at a disadvantage compared to the fossil-based alternatives. Today, biomass is used where it is available as production residue (pulp and paper industry, 80% of industrial biomass use) or if the combustion process also serves as waste disposal (clinker production, 75% of renewable waste use) [5]. The ability to compete against natural gas, fuel oil and coal in other applications is limited[46].

The cost competitiveness of electricity is even worse with current regulations in many EU countries. This can be illustrated with the example of an all-electric glass furnace. Switching from natural gas to electricity would increase energy costs to 54 EUR/MWh (based on Egenhofer and Schrefler [74]), which would result in an effective price increase of 40 EUR per tonne of saleable float glass (17% of current prices). These costs would value a tonne CO_2 with 75 EUR (with 0.53 tCO_2 mitigated), which is well within the range of emission price assumptions in long-term energy scenarios, albeit usually not before 2030 [90], [91] and even later in reference scenarios [92], [91]. As discussed above, all-electric furnaces include several side-benefits (e.g. strongly improved energy efficiency). Electricity-based steam generation faces high electricity prices compared to fossil fuels, dependence on decarbonized electricity and low capacity of current systems.

Additional biomass and electricity demand

Biomass availability is limited and its sustainability is closely tied to regional production and land use. Especially competition with other demand sectors (i.e. households, power generation and transport) will limit industrial biomass use considerably. Therefore, it seems plausible that biomass use should be favoured for applications with chemical use (e.g. as reducing agent in iron and steel or as feedstock in the chemical industry). Several estimates of biomass availability are given in recent studies and they vary according to their definition of sustainability. A considerably tight definition is given in Öko-Institut, Fraunhofer ISI [93], assuming equal distribution per capita worldwide. For Germany, this assumption yields a biomass potential in 2050 roughly equal to 2010 levels, with 110

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46 Biomass is often traded in local or regional markets and international prices do not exist. However, we assume prices in the region of 3-4 EUR/GJ for solid biomass, similar to hard coal and slightly higher than lignite. Treated, high-grade biomass (e.g. pellets) can be much more expensive, up to 8 EUR/GJ for domestic production and 12 EUR/GJ for imports [88]. For comparison, prices for natural gas in the EU in 2015 were, depending on consumption, between 7 EUR/GJ and 15 EUR/GJ [89].

TWh allocated to the industry sector. Extrapolated to the EU based on final energy demand would yield a potential of 500 TWh, which is roughly double the use in 2015 [5]. Other estimates [94] describe a five times increase of available biomass-based energy production until 2050 (83 PWh) compared to 2008, albeit on a worldwide scale. Connolly et al. [95] assume a potential of 3900 TWh to be sustainable for the entire EU28 in 2050, also based on a per capita-approach (27 GJ/person/year). Assuming the industry uses a similar share as in 2015 (25%, [5]), a potential of 975 TWh would result. For this discussion, we thus assume a sustainable biomass potential available for the industry in the EU28 (2030) between 500 TWh and 975 TWh.

This potential would suffice to cover todays demand (179 TWh) and additional 130 TWh of the energy demand in steam generation (Table 3.6) of the reviewed subsectors (168 TWh biomass use in 2015). This would equal the assumed biomass share in steam generation and furnaces of 50% by 2030 (298 TWh). The proposed measures; the replacement of PCI and coke/sinter fuel with biomass-based fuels (180 TWh) and biomass-based clinker and lime production (165 TWh); create additional biomass demand. The total industrial biomass use in 2030 sums up to 827 TWh, of which 648 TWh are additional demand compared to 2015. This demand exceeds the lower potential estimation (500 TWh) but remains below the higher estimation (975 TWh). It thus seems at least possible that the fuel switch measures to biomass could be supplied by sustainable, domestic biomass. However, these numbers include neither efficiency gains nor activity changes and their influences should be investigated in more detail.

Table 3.6: Estimation of biomass demand of the reviewed fuel switch options

Process	**Measure**	**Energy demand 2015 [TWh]**		**Additional biomass demand by 2030 [TWh][3]**	**Potential coverage with biomass by 2030[4]**	**Sustainable biomass available [TWh]**
			of which biomass			
Refinery	Replacement of natural gas	527[1]	0	158	30%	
Iron production	Replacement of PCI with biomass (blast furnace)	452[2]	0	180	40%	
	Biomass in coke production					
	Replacement of coke breeze with biomass in sintering					
Clinker production	Substitution of fossil fuels with biomass in rotary furnaces	175[2]	10	165	100%	
Lime production	Substitution of fossil fuels with biomass in shaft furnaces					
Steam reformer	Biomass gasification for fuel supply	64[2]	1	15	25%	
Steam generation and furnaces	Biomass boilers, biomass fired furnaces	595[2]	168	130	50%	
Sum		**1813**	**179**	**648**	**46%**	**500-975**

1: Based on [5].
2: Own calculations based on [5] and FORECAST model (see [96]).
3: Resulting from fuel-switch measures considered in this paper.
4: Assuming constant energy demand (no activity of efficiency changes).

Electricity would have to supply a substantial share of heating, which highlights the relevance of the electricity generation mix. Switching to electricity can only yield substantial emission reductions when the generation itself is based on renewable sources. Some scenarios [1] see renewables as dominant source of electricity already in 2030 (between 60% and 80% of generation). Still, a complete decarbonisation of the electricity supply is not expected before 2050 [97]. To facilitate the industry's decarbonisation based on electricity, rapid and ambitious deployment of renewable electricity generation is required.

The generation capacity of renewable electricity is limited. With the proposed measures, an additional electricity demand of 481 TWh would result (Table 3.7), of which the major part is located in steam generation (288 TWh) and refineries (122 TWh)[47]. The electricity demand of the entire EU28 industry was 1004 TWh in 2015 [5]. A substantial increase in renewable generation is expected and deemed possible in transformation scenarios: Zappa et al. [98]: renewable generation ranging between 1400 and 3600 TWh in 2050; Öko-Institut, Fraunhofer ISI [93]: more than doubled renewable generation in 2030 (320 TWh) compared to 2012 in Germany; Held [99]: EU28 potential of 1400 to 2000 TWh in 2050). If the sector-split of electricity consumption remained the same (36.5% industry in 2015), these estimates would yield an additional potential available to industry between 500 TWh (lower estimate of 1400 TWh total) and 750 TWh (upper estimate 3600 TWh total).

The additional demand estimates do not consider the overlap of electricity and biomass options. The identified intersection between electricity and biomass of 50 Mt or around 300 TWh is thus important as it allows using cost-effective combinations.

Table 3.7: Estimation of electricity demand of the reviewed fuel switch options

Process	**Measure**	**Energy demand 2015 [TWh]**		**Additional electricity demand by 2030 [TWh][3]**	**Potential coverage with electricity by 2030[4]**	**RES-E generation available for industry [TWh]**
			of which electricity			
Refinery	Replacement of natural gas	527[1]	36[1]	122	30%	
Steel production	Shift to secondary route (EAF)	584[1]	112[1]	11	21%[5]	
Glass production	All-electric furnaces	110[2]	25[2]	44	63%[6]	
Steam reformer	Electro-thermal reforming	64[2]	0[2]	16	25%	
Steam generation	Electric/ biomass boilers	595[2]	10[2]	288	50%	
Sum		**1880**	**183**	**481**	**35%**	**500-750**

1: Based on [5].
2: Own calculations based on [5] and FORECAST model (see [96]).
3: Resulting from fuel-switch measures considered in this paper.
4: Assuming constant energy demand (no activity of efficiency changes).
5: EAF share of 50% on steel production. Electricity share on total energy demand is lower due to different specific energy consumption compared to the primary route and other electricity uses.
6: 40% emission reduction with 50% of furnaces capacity electrified. Share of electricity is higher due to other electricity consumption.

We mentioned the economic challenges that are discussed in the literature. Apart from anecdotal examples, the additional costs incurred to the industrial energy system by these measures remain

47 The high emission reduction potential (30 Mt) of the assumed shift to scrap/EAF steel production causes relatively little additional electricity demand (11 TWh), as its specific energy consumption, being a secondary route, is about 4 times lower than the blast furnaces' [10].

unclear. Especially the interactions of short-term fuel switching and innovative processes are of interest, for example how early fuel switching may support long-term innovative processes and how transition scenarios can combine both. There is not always a clear line between technical potential (which we focus on) and economic challenges. While we define the measures identified as plausible to be within technical availability today, relevant for emission reduction until 2030 and within the existing processes, there is uncertainty on what can be done in a given period. The use of biomass-based fuels or electricity in refineries, for example, is restricted by the availability of off-gases on site. If these found a sink elsewhere (e.g. as feedstock in the chemical industry), the identified restrictions would be removed. This is indeed predominantly an economic challenge. The same is true for the use of biomass-based fuels as feedstock in steam reforming, which we excluded based on supply-side concerns. These assumptions are based on the authors' judgement.

The uncertainties involved with the chose methodology are considerable and the results can therefore only be a rough estimate. To include details neglected here (e.g. emission intensity of electricity generation and biomass supply, improvements in energy efficiency, activity changes and general economic development, policy measures, impact of discussed measures on energy efficiency and process emissions), further work should include quantitative investigations in an energy system model.

3.6 Conclusion

This paper investigates technical options to switch from fossil fuels to biomass or electricity-based heating in selected, important industrial processes. The analysis focuses on mitigation measures that are technically available today and can have a relevant impact until 2030. Fuel switch measures discussed in the literature are reviewed and a combined emission reduction potential for the investigated processes is calculated. Based on the reviewed literature, technology-readiness levels (TRLs) are estimated. Measures above TRL 5 are included in the analysis.

We found that of the 546 Mt CO_2-eq. emissions of the investigated industrial processes, 34% (185 Mt CO_2-eq.) could technically be mitigated with the identified short/medium-term fuel switch measures towards biomass or electricity by 2030. The use of biomass alone shows a potential of 165 Mt emission reduction, with the most important measures being the injection of biomass in the blast furnace (instead of pulverized coal), biomass use in rotary kilns in the cement and lime production as well as for synthesis gas for ammonia and methanol production. Electrification could realize 115 Mt CO_2-eq. emission reductions. Its potential is highest in the iron and steel industry (increased secondary steel production in EAF). Moreover, electricity may supply steam generation boilers and furnaces in other applications (e.g. melting, reheating). The potentials of biomass and electricity overlap by 93 Mt CO_2-eq.and the combined potential is 185 Mt CO_2-eq.

Fuel switch to electricity and biomass can make a substantial contribution to achieve a reduction by 2030 in line with 1.5°C warming, but very likely needs to be accompanied by additional measures like energy efficiency and also more efficient material use as well as recycling of materials. The reduction potentials investigated include measures that are technical available but not economically competitive today and determined effort is needed to integrate them into the market. In the period after 2030, innovative CO_2-neutral production processes will need to diffuse quickly to remain on a 1.5°C path towards 2050.

These innovative processes would have to address an amount of emissions that is not reachable with fuel switch (275 Mt), consisting of fuel inflexibility of existing processes and process-related emissions. Another amount (87 Mt) may not be mitigated before 2030 due to restrictions in stock exchange and feedstock availability. Additional potential could be realized by the early replacement (in contrast to natural stock exchange) of fossil steam generation installations and the availability of biomass-based fuels in high quantities for feedstock.

Considering all the identified measures, substantial GHG emissions remain, mainly consisting of process related emissions (e.g. cement and steel production) and residual fuel use (e.g. refineries, petrochemical industry). To address these emissions and achieve deep decarbonisation of industry after 2030, new feedstock and process switch to CO_2-neutral technologies (e.g. new cement types, bio-refinery) are necessary among others. The compatibility of short, medium- and long-term measures is therefore another important concern to be addressed in future research.

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4 Fuel choice in industrial steam generation: Empirical evidence reveals technology preferences[48]

Abstract

Scenario analysis of the energy system relies largely on model calculation and underlying techno-economic data. In the industrial context, the influence of behavioural aspects has been neglected or is subject to expert-judgment. Empirical evidence on technology preferences is scarce. In this publication, we present original survey results for preferences in industrial steam generation technologies in Germany. Additionally, we compare the performance of a set of preference parameters derived from these results with expert-judgment. We find that in the sample, coal- and oil-based generation is perceived as less attractive than biomass- and natural gas-based generation by a value equivalent to 4.40 €ct/kWh and 2.26 €ct/kWh, respectively, for experienced users. This effect is stronger for inexperienced users (+55%). Different results were obtained in an energy system model using these stated preferences and expert judgment (considering revealed preference data). This might hint at a shift of preferences.

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4.1 Introduction

Scenario analysis of long-term energy futures has to address multiple types of uncertainties. Assumptions on future developments are the most prominent: economic or population growth, technological advances, energy prices and many others. The direction these framework values take, determine largely the outcome of the analysis [1]. For energy models dealing with industry, the consideration of preferences in investment decisions is a rather new concept, for which empirical data are scarce. Therefore, not only the future development, but also the status is uncertain. The approach applied in this publication originates from research of private consumer behaviour, e.g. in tourism and transportation [2, 3]. Behavioural aspects have not been the focus of industry models, as decisions made by companies are thought to be highly rational and thus less influenced by individual or group-specific preferences. However, cost optimizing often does not adequately represent observed technology choice, because among others, factors like fuel handling, status-quo, emissions, future expectations and lack of information also influence the decision outcome. This shows a parallel to the much more investigated field of energy efficiency and its barriers and enablers [4, 5]. Accordingly, energy models consider preference parameters beyond cost-optimization; however, they often lack a sound empirical foundation and are instead based on "expert judgement". Few surveys have been conducted to determine preference parameters empirically (e.g. [6]). Fuel choice models and their parameters are instead often derived from top-down econometric analyses (e.g. [7]). Empirical evidence on these parameters is scarce, because samples in the industrial context are usually much smaller and harder to come by than in private households. These difficulties are amplified by the heterogeneity of industrial activity.

In this publication, we present a case study on technology choice of companies in the industry sector on the example of steam generation in Germany. Steam generation accounts for about 40% of industrial process heating demand in Germany (and Europe) [8]. We present original data on preferences for generation technologies. Based on the survey results, we derive preference parameters for technology choice and compare them with parameters based on expert judgement. We investigate which parameter set better explains the observed development in Germany during 2008 and 2016 in the energy-demand model FORECAST [9, 10]. The steam generation simulation shares elements with the fuel switch model for industrial furnaces described in more detail in [11].

The paper is structured the following way: First, the data generation, analysis and the modelling approach are presented. Second, the construction of the preference parameter sets is explained. Third, the respective model outcomes are compared against the observed development.

4.2 Method and Data

4.2.1 Survey design and results

To analyse the preferences of decision makers regarding steam generators we conducted a survey, targeted at German companies operating steam generators. The survey took place between 7/2018 and 10/2018. The resulting sample consists of 164 respondents from the branches "food processing" (n=116, 71%), "chemical and pharmaceutical production" (n=22, 13%), "paper and card-board production" (n=18, 11%) and other branches (n=7, 4%).This sample distribution is mostly similar to the distribution of companies in these branches [12] in Germany (excluding the mineral industry) [49]. For 53.0% of the respondents, investment decisions regarding steam generators are part of their professional duties (hereafter labelled 'experienced users'). 28.0% of the respondents work with steam generators although they are not directly concerned with respective investment decisions. Additional 10.4% do not work with steam generators but have done so in the past. The remaining 8.6% of the respondents have no experience with steam generators but consider it likely that they will gain such experience in the future (the latter three categories are labelled 'unexperienced users'). Respondents who stated that none of the before mentioned categories apply to them were excluded from the sample.

In the survey each respondent evaluated the attractiveness of nine steam generators. The steam generators were characterized by three attributes, whose values were generated randomly within a given range for each of the nine presented steam generators. First, the costs of steam generation in €ct per kWh (possible values: 4, 6, 8 and 10). Second, their reliability as the share of downtime during operational time (possible values: 1%, 0.5%, 0.1% and 0.01%). Third, the used source of energy, which was linked to the amount of CO_2-emissions of the steam generation by respective explanations in the survey (possible values: coal with 100% CO_2-emissions as a benchmark, oil with 80% CO_2-emissions compared to coal, natural gas with 60% of CO_2-emissions compared to coal, biomass with zero net CO_2-emissions[50]).

As the attractiveness of the steam generators was measured by a six step rating scale[51] we analysed these data by a hierarchical linear model with fixed and random effects, in which the evaluated steam

[49] NACE Rev. 2 classification were used to differentiate the branches: food (10, 11, 12), chemical (20), paper (17). From this selection, food makes up for 70.2% of the companies, chemicals for 19.3% and paper for 10.5%. The chemical industry is thus slightly underrepresented in the sample.

[50] This simplification has been made for the survey, neglecting supply chain emissions. The authors are aware that biomass may have relevant carbon footprints when effort e.g. for transport or processing is considered.

[51] The nine steam generators were presented on three pages of the online survey, and therefore coined as options (A, B, C) on each page. Accordingly, each site contained three statements 'option [A/B/C] is very attractive'. Those could be answered by: *1=fully disagree, 2=mostly disagree, 3= rather disagree, 4=rather agree, 5=mostly agree, 6= fully agree*. Please refer to Annex 1 for this section of the survey (translated from German) and the complete questionnaire in Annex 2 (in German).

generators are the micro units (cases) clustered within the respondents as macro units (nine cases per respondent) [cf. 13, 14]. The resulting model explains 76.7% of the variance in the evaluation of steam generators. We find significant effects for all three attributes that characterized the steam generators (costs, downtime, and energy source). In addition, the effect of costs depends on the experience of the respondents with investment decisions in steam generators while there are no such differences for the effects of the other attributes. In particular, an increase of costs by 1 €ct/kWh decreases the attractiveness of a steam generator by 0.263 points at the rating scale for unexperienced users while we find a decrease of 0.410 points for experienced users. For each percentage point of downtime the attractiveness of the steam generator decreases by 0.383 points. Furthermore, a steam generator powered by oil is 0.926 points less attractive than a steam generator powered by biomass. If a steam generator uses coal as energy source instead of biomass, the evaluation decreases by 1.802 points. In contrast, steam generators powered by natural gas are not evaluated significantly different from those powered by biomass. To put the energy-carrier related influence into perspective: a steam generator with average costs (7 €ct/kWh) and average downtime (0.4% of total operational time) powered by biomass is evaluated with a rating of 4.1 (rather attractive).

The interclass-correlation is .066. This indicates that only 6.6% of the variance in the evaluation of steam generators is caused by individual differences (e.g. branch or other characteristics at the respondent level) between the respondents. As described above, such differences exist regarding the relevance of costs depending on practical experience with investment decisions in steam generators. However, due to the small interclass-correlation and the limited sample size we do not analyse the causes of such differences.

4.2.2 Energy system model description

In order to test the survey results in an energy model, we use the model FORECAST. FORECAST is a bottom-up energy system model covering the demand sectors. Among others, it models the choice of industrial steam generation technologies as a discrete choice among competing alternatives. The main determinant of attractiveness in this competition is the perceived utility of the alternatives for the decision maker. This utility is influenced by characteristics of the technology (e.g. investment, fuel costs, available dimension, co-generation capabilities …), framework condition (e.g. taxation, feed-in tariffs) and the decision makers' heat demand and preferences. The preferences serve as modifier to the total generation costs and influence the perceived utility of the technology. For example, a coal-based steam boiler may be more attractive where coal is already used in a different context. This may be attributed to existing infrastructure, personnel or general experience. At the same time, fuel prices may be different for some market participants than observable on the macro-level (e.g. biomass in paper industry, natural gas and fuel oil in refineries).

The preferences are coded in parameters (Annex 5). They depict the perceived utility U_k in relation to the plain generation costs based on macro- and techno-economic data according to equation 1. It contains ε_j as market homogeneity, $c_{i=k}$ as costs of an individual technology and $\overline{c_i}$ as average costs of all technologies available to the decision maker.

$$U_k = \varepsilon_j * \frac{c_{i=k}}{\overline{c_i}} \quad (1)$$

The decision for a specific technology is made according to equation 2; with the choice probability *π* for an individual technology *k* from all available technologies *i* as function of perceived utility *U*. This approach is similar to and partly based on [6, 15].

$$\pi_k = \frac{\exp(U_{i=k})}{\sum_i \exp(U_i)} \quad (2)$$

The choice probability is a value between 0 and 1 for each technology and sums to 1. The market homogeneity governs the impact of price differences. High homogeneity increases the impact, as market participants tend to favour the highest-utility option more. However, except for extreme values, all available options will be present in the market, which allows representing niche-applications. For this particular application, a medium-to-high value (7) of the market homogeneity has been chosen, which proved to work with the expert-based parameter set[52]. To illustrate its effect: this value results in a doubled chance to select a given technology over a technology with 10% increased costs. Note that the choice probability relation follows an s-curve, i.e. is most sensitive in the middle range. Thus, decreasing the costs of a very cheap technology does not greatly improve its market diffusion, while cost variations of close competitors can influence it strongly. See [16] for further model description.

4.2.3 Energy system model implementation

For the construction of a preference parameter set, the survey results must be interpreted accordingly. The central finding of the survey is, that coal- and oil- based steam systems are evaluated significantly worse than natural gas- and biomass-based systems. For experienced users, this is worth a flat margin of approximately 4.40 €ct/kWh (oil: 2.26 €ct/kWh). This value is calculated by dividing the change of attractiveness due to energy carrier (coal: 1.802 points, oil: 0.962 points, compared to biomass/natural gas as baseline) by the change of attractiveness due to a price increase of 1 €ct/kWh. For experienced users, this price increase is 0.410 points. For inexperienced users, it is weaker (0.263). This means that experienced users value the attractiveness due to price increases higher and, in turn, those due to energy carriers lower. Hence, the effect of energy carrier on technology choice (in monetary terms) is weaker for experienced users.

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[52] While the concept of market homogeneity can be qualitatively described (e.g. by the number and size of companies active in the market), the quantification for the model is an assumption and should be treated with caution. Qualitatively, this values favours the most economic option but still allows for niche applications. This is similar to the approach [6] pursued with a comparable model.

For the energy system model analysis, we apply only the weaker energy carrier related effect of the experienced users. For the discrete choice-based model, this means that the perceived utility for both technology options is equal, when biomass shows generation costs 4.40 €ct/kWh higher than coal. Due to survey limitations, some assumptions must be made for the model implementation:

- The energy carrier preferences have been collected for 'steam generation systems' and are applied for both CHP and boiler systems equally, each based on their energy carrier.
- Minor energy carriers with similar emission factors as the ones included in the questionnaire (e.g. biofuel compared to biomass; waste compared to coal) are assumed to have a similar attractiveness[53].
- The preference-based price increase of 4.40 €ct/kWh (coal) and 2.26 €ct/kWh (oil) is applied as a factor, rather than a flat value. For example, coal-based steam boilers show an average generation price slightly above 2 €ct/kWh between 2008 and 2016 (Figure 4.1). Considering the preferences, the price should increase by 4.40 €ct/kWh (to 6.40 €ct/kWh). Hence a factor of 3.2 (rounded) is applied. For oil (average price between 2008 and 2016: 6 €ct/kWh), this calculation yields a factor of 1.4 (rounded). The respective generation costs (c_i in equation 1) are multiplied by these factors in each year of the model calculations. The relative price differences are maintained throughout the simulation.

[53] The model requires input for all considered energy carriers (27), but not all of them could be included in the survey. The energy carriers represented by this analogy are of limited importance for the overall picture (in total 25% of the investigated energy demand, with the biggest shares for district heat (10%) and non-renewable waste (5%). The assumption is made for modelling purposes only.

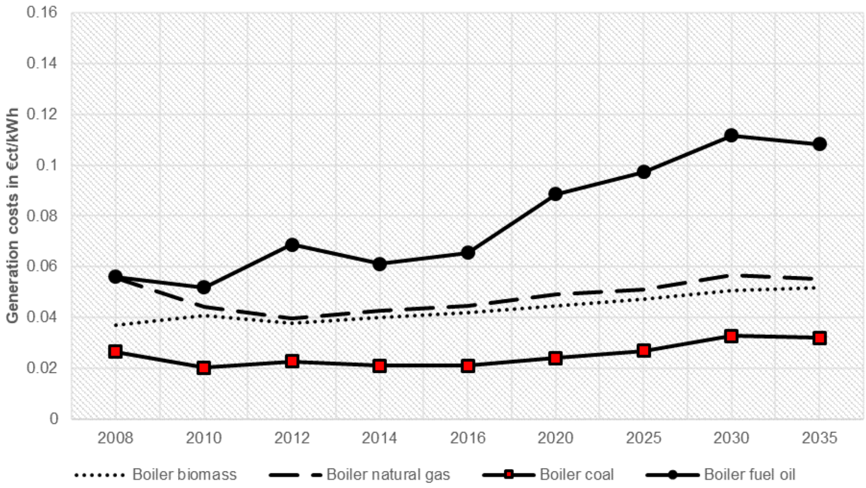

Figure 4.1. Heat generation costs of selected technologies (Germany)[54]

Table 4.1 shows the resulting preference parameter sets (expert judgment and survey data). The presented factors are applied to the generation costs (e.g. a factor of two doubles the generation costs) which are used to determine the utility (and hence choice probability) of the given technology. In the survey-based set, natural gas and biomass are assigned the factor 1; coal is assigned the factor 3.2, oil 1.4. The expert-based parameter set has been developed over the last years specifically for the model. Its main considerations include operation, required infrastructure, available dimensions and macro-trends (e.g. observed declining fuel oil use in all industrial subsectors and increasing coal use in many industrial subsectors).

54 The heat generation costs have been generated with the energy system model FORECAST. In this publication, they should be treated as assumption.

Table 4.1: Parameter set comparison (energy carriers not available in the survey data set assigned to similar, available energy carriers, indicated in brackets)

Technology	Energy carrier	Expert-based	Survey-based
Boiler	Electricity	1	1
	Natural gas	1	1
	Coal	0.8	3.2
	Oil	7	1.4
	Biomass	1	1
Steam turbine	Oil	4	1.4
	Biomass	1	1
	Natural gas	1	1
	Coal	1	3.2
ICE/gas turbines	Oil	4	1.4
	Natural gas	1	1
	Biomass	1	1
Heat pump	Natural gas	3	1
District heating	Other (natural gas)	1	1
Fuel cell	Natural gas	1	1

4.3 Results and discussion

The scenario underlying the following calculations is based on [17]. It develops a 'reference'-scenario with limited transformation, in which fossil fuels are still relevant in 2035. However, focus of this investigation are the relative differences between the parameter sets. Figure 4.2 shows the resulting energy demand in both variations for the most relevant energy carriers (80% of total), for the start year 2008, the end of the empiric data [18] 2016 and the end year 2035. The energy carriers biomass, district heating, electricity and natural gas behave similar in both parameter sets. Coal and fuel oil however, show diverting developments. These results are in line with the expectations due to the parameters changes (increased price for coal, reduced price for oil in the survey-based parameter set).

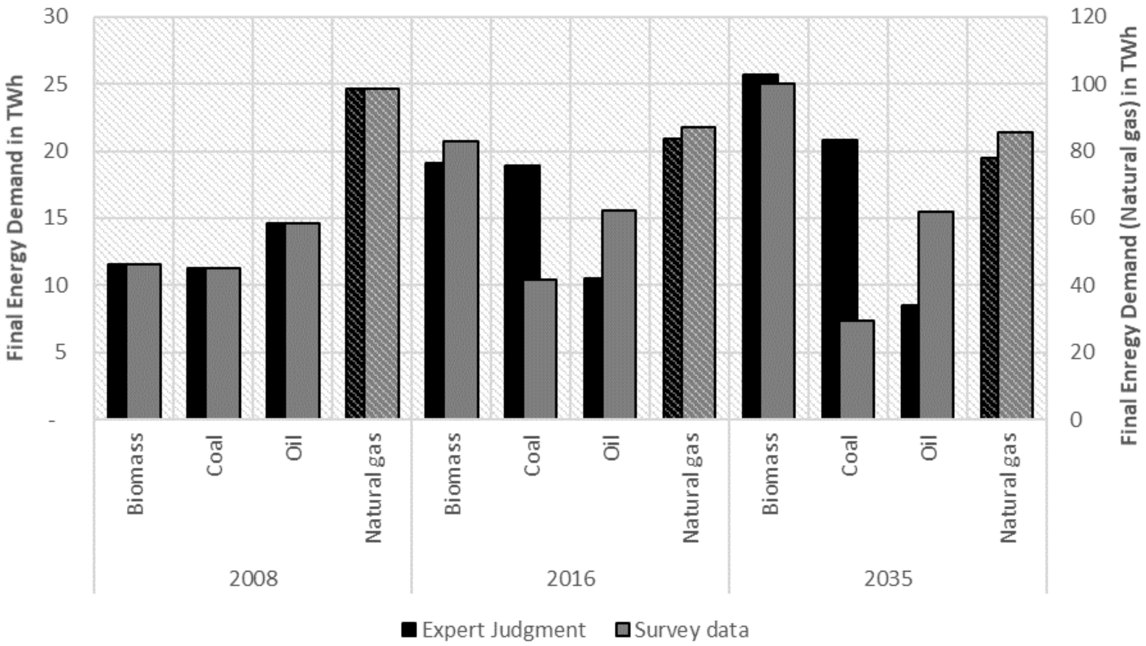

Figure 4.2: Final energy demand of selected energy carriers for the parameter set variation (Germany), Natural gas on secondary axis

Figure 4.3 compares the change in energy demand with the historical development, reflecting the difference between model results and energy balance. A positive value indicates a higher use of this energy carrier in the model than in the energy balance (hence an overestimation of its attractiveness) and vice versa. The survey-based parameter set increases this difference for coal and oil and reduces it for biomass and natural gas. This means that the survey-based parameter set underestimates the use of coal in steam generation, at least in the observed period of 2008-2016. Regarding energy system models-educated design of climate policies, this could create a situation in which the demand for action is underestimated. On the other hand, overestimated coal use (present, though not as strong, in the expert judgment parameter set) can induce inefficiencies. However, the survey data describes the preferences of the sample during the survey (July to October 2018) and the expert judgment data includes information from a longer period, including for example the observation that coal use in industry increased during the last decade in Germany. Therefore, the different preferences do not necessarily contradict each other but might indicate a shift of preferences.

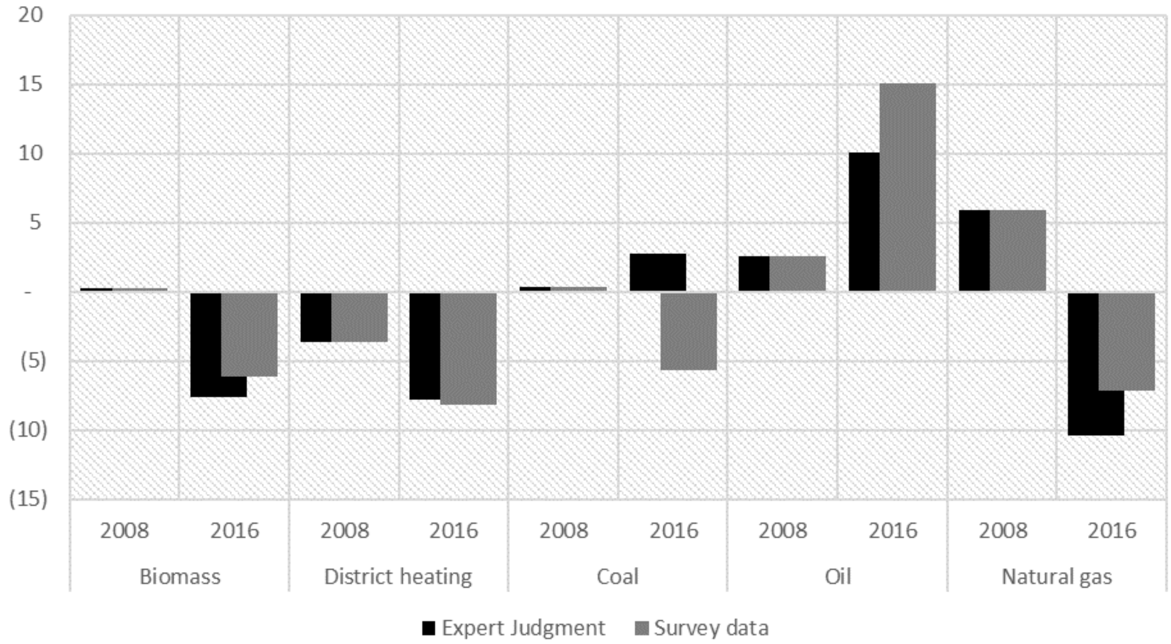

Figure 4.3: Difference of final energy demand (model results - energy balance)

The sample size did not allow for the identification of subsector-dependencies (e.g. higher preference for biomass in the paper industry). The questions were designed to focus the respondents towards their professional opinion and create a situation close to actual investment decisions. To account for a possible bias of the artificial decision-situation we compared our survey-derived parameters with expert-based parameters (which are partly based on observed preferences). However, further research is needed to support either of the approaches.

Despite these difficulties, the presented results are an improvement of the scarce data availability in this field. Further effort should focus on reproducing these results and add the opportunity to investigate sectoral heterogeneity by larger samples.

4.4 Conclusions

Two conclusions can be drawn from this case study: First, preferences regarding the energy carrier choice in steam generation do exist (coal < oil < biomass = natural gas). The study succeeded in finding empirical evidence, which is so far very scarce. We find that in the sample, coal- and oil-based generation is perceived as less attractive than biomass- and natural gas-based generation by a value equivalent to 4.40 €ct/kWh and 2.26 €ct/kWh, respectively, for experienced users. This effect is stronger for inexperienced users (+55%). However, no such preference can be observed regarding the associated emissions, as such a relation should create a difference between biomass and natural gas. This is especially interesting since the survey instructions explicitly referenced the relative emission factors of the energy carriers.

Second, the preferences identified are strong enough to influence the results of energy system models not only quantitatively, but also on a qualitative level, as they can turn the trend of energy carrier use around. A comparison with expert-judgment, partly based on observed behaviour, showed relevant differences. This might indicate that preferences are shifting compared to previous decades.

The results obtained from the different preference parameter sets justify differing policy recommendations even for the same scenario definition. Further research should try to combine the strengths of the approaches. Investigating the reason for the deviation between stated and revealed preferences could yield valuable insights into the decision making process.

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5 Inter-fuel substitution in European industry: a random utility approach on industrial heat demand[55]

Abstract

As the majority of industrial emissions stems from heat generation, the choice of fuel is, next to energy efficiency, one of the tools to influence climate impact (and security of supply) in industrial energy use. At the same time, the choice of fuel is not only a matter of price but of the furnace, it is used in. Top-down models often struggle to include technological explicitness, which is especially important to represent the heterogeneous structure of industrial energy demand. In this paper, an approach to apply a discrete choice model to industrial high temperature energy demand is presented. The model's parameters are estimated based on observed fuel choices. The model exhibits an average coefficient of determination of 0.45 when compared to a constant fuel use from 2002-2013 in major countries of the European Union. Results suggest that energy carriers are perceived very differently by industrial consumers.

[55] This chapter has been published in Journal of Cleaner Production as *Rehfeldt, M.; Fleiter, T.; Worrell, E. (2018): Inter-fuel substitution in European industry: a random utility approach on industrial heat demand.*

5.1 Introduction

Heating and cooling accounts for half of the European Union member states (EU28) energy demand. Of this, industrial high temperature process heat (defined here as above 500 °C), makes up for about 1,100 TWh (47 %) *(Rehfeldt et al. 2017* and with a comparable approach *Naegler et al. 2015)*. A vast majority of this energy is supplied by fossil fuels. An important dimension of energy use is the choice of energy carrier, often closely related to the technology choice. Although the purpose of supplying energy, or more specifically heat, to an industrial process is the common ground for all utilized energy carriers, it is evident that not all of them are perfect substitutes. Especially in the context of emission reduction, the choice of fuel use plays a major role (*IPCC 2014*). Inter-fuel substitution describes how and to what degree energy carriers can be substituted with each other. It is discussed with regard to climate change (*IPCC 2014*, also *Newell, Raimi 2014* in the context of the U.S. shale gas development), health issues (*IEA 2016*), security of supply *(European Commission 2014a, b*) and cost effectiveness (*Gessa-Perrera et al. 2017*).

While energy efficiency and its diffusion in the industry as a whole as well as in individual processes is well researched, characterization of processes is often focused on specific energy demand and their energy efficiency. Examples include *Worrell et al.* (*2000, 2010*) in the context of the chemical industry and the iron and steel industry or the best available techniques reference documents (*BREF 2001-2018*) that describe best the available technologies for several industrial applications and sectors. However, developments in some processes show that incremental efficiency improvements reach technical or physical limits, for example the use of reducing agents in blast furnaces *(Fleiter et al. 2013)*. The choice of energy carriers is seldom addressed.

The use of energy models in all forms has become an important tool in both research and policy advise, especially for the analysis of increasingly complex energy systems. While analyses of energy efficiency focus on technology-rich bottom-up models, econometric models are often used to investigate the fuel mix (see for example *Stern 2010* for a meta-analysis of approaches). These top-down approaches rarely account for technological properties of industrial processes. Therefore, technological restrictions are often neglected in favour of macro-economic effects and analysis. Neglecting technological limitations can lead to overestimated potentials for the use of biomass, waste, recovered heat and inter-fuel substitution in general. Jones (*1995*) investigated the impact of non-substitutable fuels in his econometric analysis of the U.S. industrial energy demand between 1960 and 1992 by excluding non-energy use (coking coal, feedstock and lubricants). He showed that the estimated price elasticities changed significantly compared to an approach without these technological considerations.

The purpose of this study is therefore to develop an approach to include technological detail into fuel switch considerations of energy demand models. To that end, it answers two main questions. Firstly, a decision model for the fuel choice in industrial processes is proposed, to define how market-driven inter-fuel substitution can be explained. Secondly, the decision model is included in an energy demand model, to answer the question, how top-down and bottom-up approaches can be combined.

The question is approached by combining technological data of individual processes (e.g. specific energy consumption, temperature level of energy demand) and top-down statistics on subsectoral level (energy balances). The decision model is based on the idea of random utility maximization (RUM). The main hypothesis of this approach is that decision makers maximize their perceived utility, described via directly observable properties (e.g. the fuel price) and not directly observable consumer preferences. The preferences of decision makers may be defined by technological, economical or personal circumstances. They generate heterogeneous decision outcomes among countries and subsectors.

This publication therefore contributes to the topic of inter-fuel substitution by considering technological detail of industrial processes already in the model construction. The bottom-up character of the model system yields higher detail than the usual (econometric) analyses. This can increase the insights gained from energy system models and the policy recommendations derived from them.

The paper is structured as follows. In section 2, the applied simulation model is described and the main input data sets (observed energy carrier use and price from 1992 – 2013) are presented. The model is applied to historic energy market shares in the EU28. This yields parameters that represent heterogeneity and behavioural differences among the investigated groups (countries and subsectors), which are presented in section 3. The paper concludes in section 4 with a discussion of the methodology and the generated preferences as well as alternative approaches that may complement them.

This publication is accompanied by supplementary data that include the full parameter estimations for selected individual countries and country groups, subsectors and energy carriers.

5.2 Data and methods

5.2.1 Model description

The model is based on a logit-approach of a random utility methodology, as theoretically described by Train *(2002)* and McFadden *(1974, 2000)* and applied to the household, transportation and industrial sectors in the bottom-up/top-down hybrid model CIMS *(Rivers et al. 2003)* and in an industrial context for the IEA's World Energy Outlook *(Kesicki, Yanagisawa 2014)*. Some key elements for the industrial context (heterogeneity and behaviour) are presented in detail by McCollum et al. *(2016)* in respect to mobility.

The following factors are represented explicitly in the model. Other influences are either considered implicitly or neglected. They are discussed at the end of this article:

- Energy carrier price
- Priced CO_2-emissions (as tax or trading scheme)
- Market homogeneity of the sectors
- Existing infrastructure and technical properties of industrial processes, expressed as preferences

Figure 5.1 shows a visualization of the fuel switch model. The market share consists of price considerations and implicit technological and behavioural influences on the subsector level (e.g. iron and steel industries, non-metallic minerals industries), represented by the model parameters. To include explicit technological data, the process level (e.g. blast furnace operations in iron and steel industries) is considered in the model. It introduces an evaluation of individual fuel properties like heating value as well as non-substitutable fuels in processes. This imposes technological limits to fuel switch and enhances the top-down approach. However, this paper focuses on the model description and the definition of the model parameters, as presented in Figure 5.1.

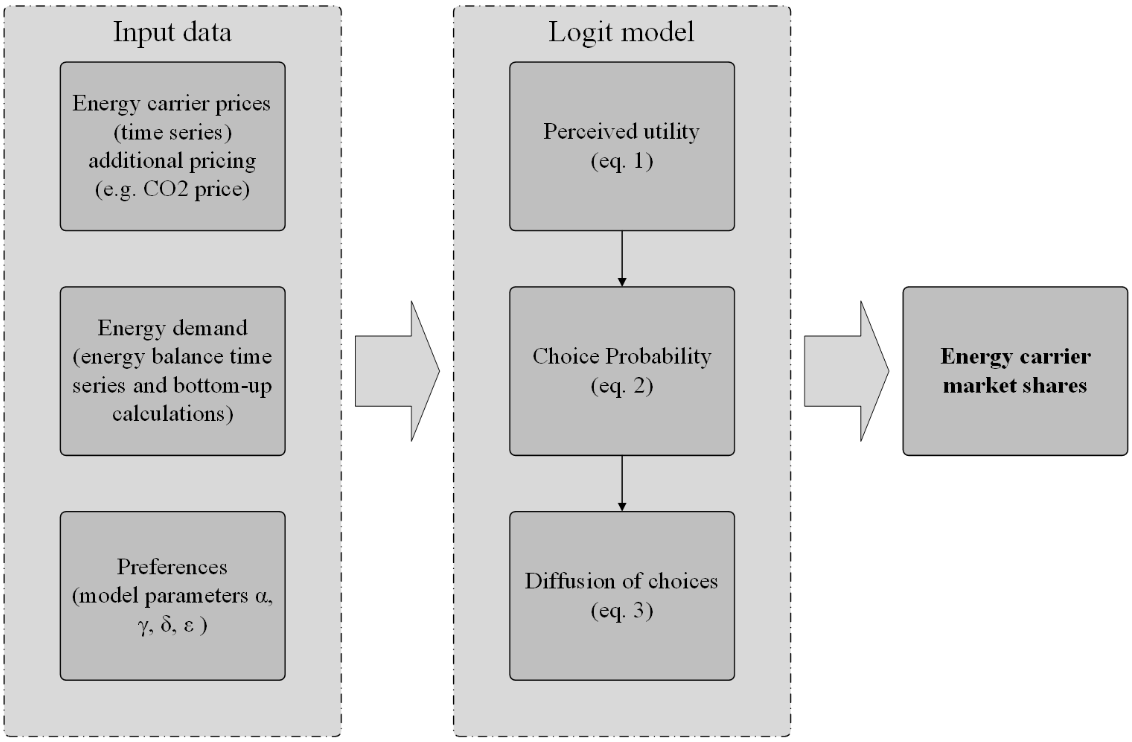

Figure 5.1: Representative structure of the fuel switch model

The dimensionless *perceived utility U* of energy carrier *i* in sector *j* for any given year and country is defined according to equation (1) (modified from *Kesicki, Yanagisawa 2014*).

$$U_{i,j} = \varepsilon_j * \left[\alpha_{i,j} * \frac{(p_i - \bar{p})}{\bar{p}} + \gamma_{i,j}\right] \quad (1)$$

With:

- ε_j as market homogeneity in sector j
- $\alpha_{i,j}$ as price sensitivity towards energy carrier i in sector j
- p_i as price of energy carrier i
- $\bar{p}$ as simple average (unweighted) price of all energy carriers
- $\gamma_{i,j}$ as intangible cost/benefit of energy carrier i in sector j

Note that compared to the work of Kesicki, Yanagisawa *(2014)*, the time-dependent term in the utility calculation has been removed.

The assumed main driver of fuel switch is the relative price difference (*Azar 2011*); that is the ratio of the price difference of an energy carrier and the simple (unweighted) average of all available energy carriers' prices ($\frac{(p_i - \bar{p})}{\bar{p}}$). An energy carrier that is more expensive than the average of all energy carriers will thus yield a lower utility and seem less attractive. This relates to the economic theory of substitute goods, immediately retaining the notion that "*the consumer is not seeking gas or oil as such but energy*", as Asche et al. *(2012)* put it. However, in industrial applications, this assumption must be modified to consider process specific requirements. It may very well be that the industrial consumer *does* seek gas as such because of strong technical preferences. This is modelled by modifying the relative price difference with an energy carrier and sector specific coefficient α which describes price-related preferences. Hence, shifts of price differences may be seen as less relevant for some energy carriers than for others when evaluating their utility. For example, natural gas is in general more expensive than coal (per unit of energy) but still used extensively.

The parameter γ reflects a structural element of energy carrier choice, which is unrelated to pricing. This may be the existing infrastructure both on-site (distribution and conversion systems) and around it (transport options like pipelines, rivers, rails) as well as other factors (expertise in specific technologies, organizational bias, long-term supply contracts, technical requirements of processes, regulations due to plant location).

ε is the market homogeneity[56] and describes how transparent the entire relevant market in a sector is *(Rivers et al. 2003)*. For very homogeneous markets, one can assume that individual market participants have good knowledge about available technologies, energy carriers, manufacturers and suppliers; they consequentially are more likely to choose the alternative with the highest utility. High homogeneity values thus create markets that are dominated by few or even a single energy carrier, while low values blur the perceived differences. In model terms, the parameter depicts how much impact observed data and preferences have on the actual perceived utility. Additional information, discussion and interpretation of the parameters can be found in 4.3.

The logit-approach (equation 2) yields the *choice probability* π for an individual energy carrier *k* from all available energy carriers *i*, in sector j as a function of the perceived utility *U*. The choice probability can be described as a sigmoid curve over the utility. A higher utility yields a higher choice probability (but with diminishing returns for very high values). Note that this does not immediately equal the market share.

$$\pi_{k,j} = \frac{\exp(U_{i=k,j})}{\sum_i \exp(U_{i,j})} \qquad (2)$$

The choice probability according to equation (2) is fed to a diffusion function given in equation (3), modified based on Kesicki, Yanagisawa (*2014*). The difference between the choice probability and the actual market share is defined as potential. Thus, the realization of the choice probability potential for fuel switch slows down as the potential difference decreases. Diffusion in this context is defined as conformity of the actual market share (*Share*) and calculated choice probability (π). Due to delaying factors, mainly stock turnover periods,

56 The terms "homogeneity" and "heterogeneity" here are used to describe different concepts: While "market homogeneity" speaks of a property of the observed group (measuring the aggregated degree of information about the group a member of it can have), "heterogeneity" speaks of a model property (the ability to differentiate among groups). They are therefore of different quality and should not be confused.

changed choice probabilities do not instantaneously convert to the market share of energy carriers. Instead, only a certain proportion of the difference between last year's market share and the current choice probability translates into a new market share in any given year (given by the diffusion speed parameter δ).

$$\mathrm{Share}(i,j,t) = \mathrm{Share}(i,j,t-1) + \delta * \left(\pi(i,j,t) - \mathrm{Share}(i,j,t-1)\right) \quad (3)$$

With:

- $\mathrm{Share}(i,j,t)$ as market share of energy carrier *i* in sector j in year *t*
- $\mathrm{Share}(i,j,t-1)$ as market share of energy carrier *i* in sector j in year *(t-1)*
- $\pi(i,j,t)$ as choice probability of energy carrier *i* in sector j in year *t*
- δ as diffusion speed parameter ($0< \delta<1$)

5.2.2 Input data

The model combines two data sets of the time series to determine the parameter price sensitivity α, structural factor γ, diffusion factor δ and market homogeneity ε:

- Energy carrier price from 1992-2013 (*OECD/IEA 2000-2016*)
- Energy carrier market shares (*Eurostat 2017*)

Energy carrier price time series published by OECD/IEA (*2000-2016)* for the energy carriers light fuel oil, heavy fuel oil, natural gas and steam coal in industry on the country level, including taxes, are used for model calibration. The resulting energy carrier prices are shown in Figure 5.2 (example for Germany). Other energy carriers, that are not included in these time series, had to be estimated based on these figures. Table 5.1 shows relations and the coupling of other energy carriers used where prices are not included in OECD/IEA (*2000-2016*). As an example, time series on solid biomass prices are not available. The assumed price development for biomass is estimated to be related to the price path of coal, increased by the factor 2. Thus, the price for solid biomass will always be two times higher than the price for coal (before taxes or CO_2 pricing) in a given country. Stack gas, on the other hand, is coupled to the price development of natural gas with a factor of 0.1 due to its low heating value.

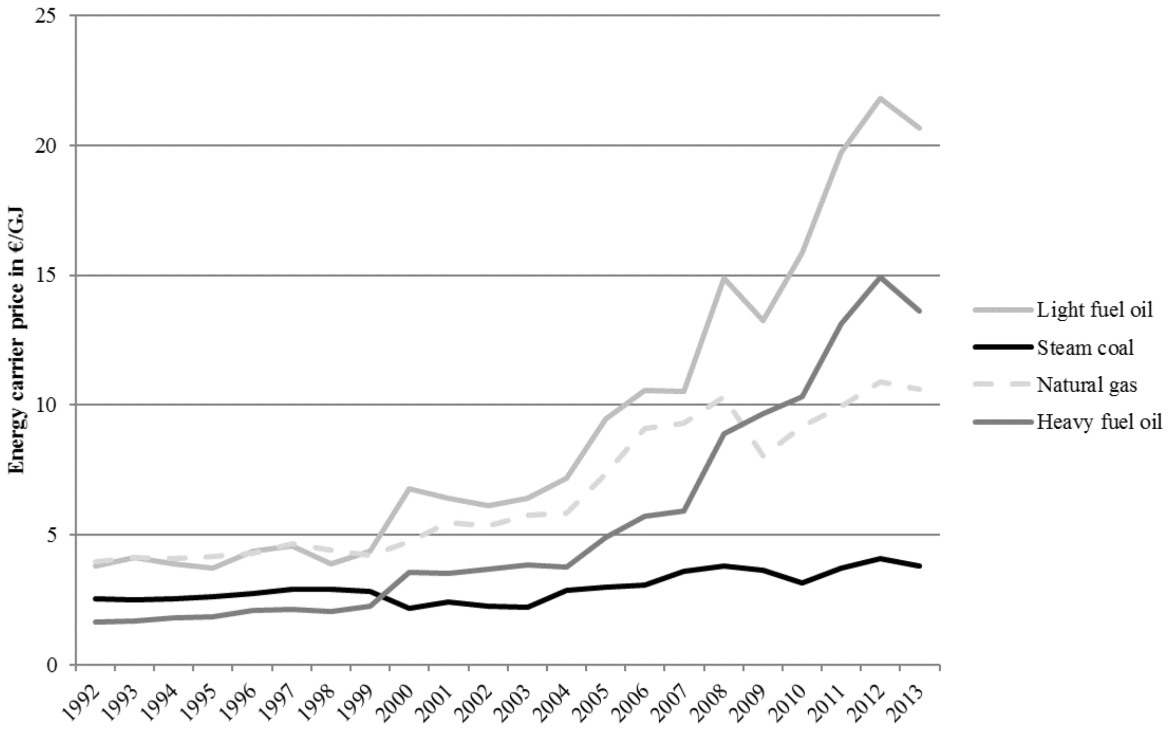

Figure 5.2: Energy carrier prices (own illustration, data source: *OECD/IEA 2000-2016*) used for model calibration, example for Germany

Table 5.1: Price path estimates for other energy carriers

Coupled energy carrier	**Base energy carrier** *(OECD/IEA 2000-2016)*	**Factor**
Derived gases	Natural gas	1
Waste	Natural gas	0.1
Stack gas	Natural gas	0.1
Biofuels liquid	Light fuel oil	1
Coke	Coking coal	1
Biomass solid	Steam coal	2
Lignite	Steam coal	0.5
Hard coal	Coking coal	1

5.2.3 Model fit

Based on the data presented in the previous sections, the discrete choice parameters α, β, γ and δ are found via a regression using ordinary least squares. These parameters implicitly reflect preferences in sectors and countries regarding the choice of energy carriers. As such, they are regarded as stable over time. The following restrictions are applied to the model regression (also see discussion):

- $-10 < \alpha < -1$ (fuels)
- $-10 < \alpha < -0.1$ (electricity)
- $0 < \gamma < 10$
- $0.1 < \delta < 1$
- $0.1 < \varepsilon < 5$

The model fit inverts the model workflow as presented in Figure 5.1, as it finds model parameters that fit an observed market share development (Figure 5.3).

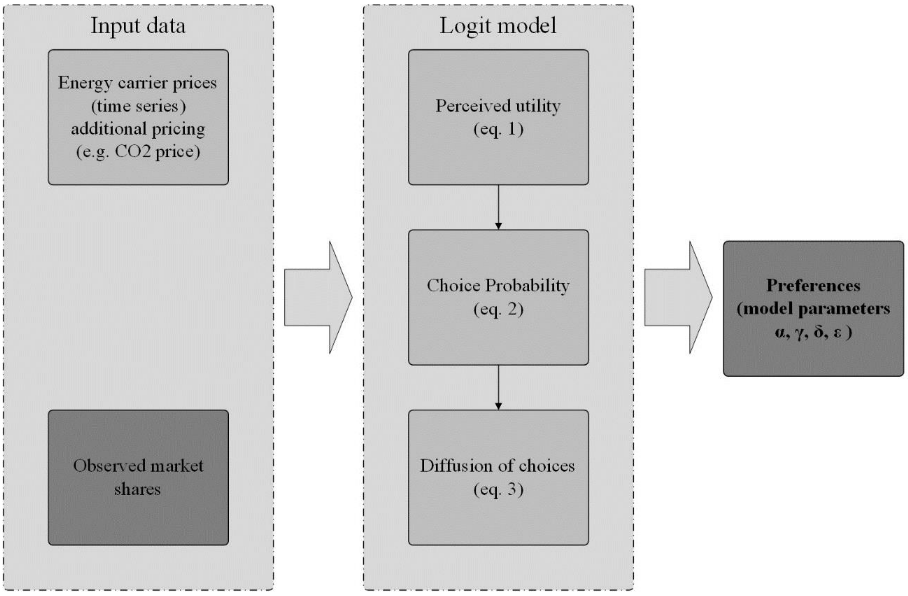

Figure 5.3: Workflow during model fit

5.2.4 Calculation examples

To illustrate the model workflow, two examples are given, both for the case of Germany: the calculation of the actual market share and the model estimate for the same historical year.

Actual energy carrier market shares for the industrial sector in the period 1992-2013 are obtained from Eurostat energy balances *(2017)*. The differentiation between high-temperature and low-temperature processes is based on [*Rehfeldt et al. 2017*], who present a list of industrial processes and their temperature profile. From these processes, only the energy demand above 500 °C is considered in the fuel switch model. An example data set for the blast furnace process is given in Table 5.2. The calculation is done as follows: Based on the specific energy consumption (SEC) of 11.64 GJ/t and the production (activity) of 28,872 kt, (*WorldSteel Association 2013*) the total modelled energy demand in blast furnaces in Germany 2015 is 336 PJ. Due to the assumed temperature profile, 87 % of this energy is considered high temperature heat demand. The process "blast furnace" belongs to the industrial subsector iron and steel, with an energy carrier share[57] reported by Eurostat (*2017*) on the subsector-level of 30 % hard coal, 17 % natural gas, 20 % coke, 15 % stack gas and others (Germany 2012). As a result, the energy demand considered in the fuel switch model consists of 101.0 PJ hard coal, 58.4 PJ natural gas, 68.1 PJ coke, 49.9 PJ stack gas and others. Energy carriers that cannot supply high temperature heat (district heat, solar energy, ambient heat) are excluded. The same is done with all other processes in the respective subsectors (e.g. for iron and steel: coke and sinter production, electric arc furnace, converter and rolling of steel). The sum of these processes is calibrated to statistical top-down values and used as subsectoral energy demand.

Table 5.2: Process data "blast furnace" (*Rehfeldt et al. 2017*)

Process	SEC fuels (GJ/t)	Activity Germany 2015 (kt)	<100°C	100°C - 200°C	200°C - 500°C	500°C - 1000°C	>1000°C	Based on
Blast furnace	11.64	30,054	0.01	0.01	0.11	0.2	0.67	Arens et al. 2017, WorldSteel Association 2013, Eurostat 2017

The fuel switch model estimates market shares on the subsector level. It starts with a statistical year and calculates the market shares of the next year based on the model parameters and price changes. For Germany in 2012, the calculation for natural gas use in the iron and steel industry is[58]:

The market share of natural gas in 2011 is 17.24 %. Its price is 11.97 €/GJ, the average price of all considered energy carriers is 11.73 €/GJ. In 2012, the price of natural gas changes to 11.06 €/GJ, the average price changes to 11.87 €/GJ. With the parameters used for natural gas in the German iron and steel subsector (price sensitivity α: 3, structural factor γ: 9.6, and market homogeneity ε: 0.64), equation 1 yields an utility of:

$$\mathrm{U}_{Natural\ gas, Iron\ and\ steel} = 0.64 * \left[-3 * \frac{(11.06 - 11.87)}{11.87} + 9.6\right] = 6.275$$

The sum all energy carrier's exponential utility (each calculated the same way) is 2,768, thus equation 2 yields the choice probability:

57 Energy carriers are aggregated, e.g. several types of coal products reported by Eurostat belong to "hard coal" and "lignite".

58 As the model calibration starts in 1992, all market share values given are model results. The representation includes a small precision loss.

$$\pi_{\text{Natural gas,Iron and steel}} = \frac{\exp(6.275)}{2{,}768} = 19.18\ \%$$

With the diffusion function (equation 3) and the diffusion parameter (diffusion factor δ: 0.1), the market share is:

$$\text{Share}(\text{Natural gas, Iron and Steel}, 2012) = 17.24\ \% + 0.1 * (19.18\ \% - 17.24\ \%) = 17.43\ \%$$

The market share increases because the relative price of natural gas, compared to the alternatives, has decreased. Compared to the choice probability of the same year (19.18 %), there still is a considerable potential for an additional fuel switch. However, this potential is realized over time, given stable price differences.

5.2.5 Process level integration

Based on the process level approach (explained in more detail in *Rehfeldt et al. 2017*), the price-related market share is modified to represent technological limitations. An example is the minimal required coke use in blast furnaces or the use of process gases in refineries. A certain share of the process' energy demand can be reserved for coke. Thus, only the remaining energy demand is calculated using the economic approach. The same can be done for the maximal use of energy carriers, e.g. low caloric fuels or fuels with limited availability (waste, biomass). As this, as opposed to the economic approach, is based on processes, a higher level of technological detail can be included.

5.3 Results

5.3.1 Revealed Preference Parameter

The model fit yields parameters that modify the utility of the energy carriers. Without considering a fuel switch, one could assume that the market shares of energy carriers remain constant. The benefit of the model is therefore estimated in a comparison between these constant market shares and the model results. It is expressed as a coefficient of determination, stating what portion of the difference between the constant average market share and the real development could be explained with the aid of the model. The values given in Table 5.3 thus do not show how much the model results resemble reality, but how much better the model performs compared to the simple assumption of constant market shares. The coefficient of determination has been calculated according to Equations (4-6).

$$R^2 = 1 - \frac{SS_{residual}}{SS_{total}} \quad (4)$$

with:

- - $SS_{residual}$ the sum of squares of the model
- - SS_{total} the sum of squares of the compared model (constant average)

$$SS_{residual} = \sum_{y=1}^{n} \sum_{i=1}^{n} \left(\widehat{MS}_{y,i} - MS_{y,i}\right)^2 \quad (5)$$

with:

- - $\widehat{MS}_{y,i}$ modeled market share of energy carrier i in year y
- - $MS_{y,i}$ actual market share of energy carrier i in year y

$$SS_{total} = \sum_{y=1}^{n} \sum_{i=1}^{n} \left(\overline{MS}_{i} - MS_{y,i}\right)^2 \quad (6)$$

with:

- - $\overline{MS}_{i}$ constant average market share of energy carrier i
- - $MS_{y,i}$ actual market share of energy carrier i in year y

Table 5.3: Coefficients of determination (R^2) for the full model compared to constant average energy carrier market shares during the calibration timeframe (1992-2013)

R^2	Iron and steel	Non-ferrous metals	Paper and printing	Non-metallic mineral products	Chemical industry	Food, drink and tobacco	Engineering and other metal	Other non-classified	average R^2
Austria	**0.27**	0.82	0.65	0.70	**0.26**	0.72	0.71	0.79	0.62
Belgium	0.41	0.64	0.81	0.55	0.97	0.90	0.80	0.35	0.68
Bulgaria	0.39	0.56	0.31	0.62	0.46	0.81	0.87	0.71	0.59
Croatia	**0.22**	0.54	**0.24**	0.77	0.67	0.89	**0.28**	0.66	0.53
Czech Republic	**0.30**	0.58	0.67	0.81	**0.20**	0.91	0.86	0.35	0.59
Denmark	0.56	-	0.75	0.77	0.80	0.66	0.80	0.76	0.73
Finland	0.60	0.73	0.88	0.86	0.72	0.55	0.92	0.72	0.75
France	**0.20**	0.78	0.51	0.51	0.47	0.65	0.84	**0.15**	0.51
Germany	0.64	0.83	0.66	0.64	0.56	0.96	0.88	0.61	0.72
Greece	0.85	0.59	0.89	0.90	0.58	0.82	0.63	0.57	0.73
Hungary	0.61	0.84	0.43	0.70	0.81	0.59	0.72	**0.28**	0.62
Ireland	-	0.93	**0.02**	0.40	0.63	0.74	0.79	0.71	0.60
Italy	0.38	0.52	0.64	0.78	0.40	0.35	0.60	0.66	0.54
Latvia	-	**0.26**	**0.14**	0.75	0.71	0.87	0.65	0.81	0.60
Lithuania	0.43	-	0.49	0.92	0.46	0.86	0.72	0.86	0.68
Luxembourg	0.84	-	-	0.66	0.84	0.62	-	0.73	0.74
The Netherlands	0.83	0.91	0.50	0.74	0.82	0.69	**0.15**	0.41	0.63
Poland	**0.21**	0.67	0.79	0.69	0.57	0.81	0.48	0.53	0.59
Portugal	0.79	0.78	0.91	0.88	0.86	0.85	0.85	0.90	0.85
Romania	0.37	-	0.49	0.72	0.37	0.38	0.32	0.40	0.44
Slovakia	0.57	0.57	0.84	**0.27**	0.45	0.77	0.84	0.44	0.59
Slovenia	**0.17**	**0.21**	0.46	0.57	0.61	0.69	0.56	0.49	0.47
Spain	0.56	0.69	0.76	0.56	0.94	0.82	0.48	0.86	0.71
Sweden	0.66	0.35	0.69	0.49	0.85	0.80	0.63	0.50	0.62
The United Kingdom	0.84	0.79	0.96	0.50	0.82	0.89	0.86	0.51	0.77
average R^2	0.51	0.65	0.60	0.67	0.63	0.74	0.68	0.59	0.64

An average coefficient of determination of 0.64 can be observed, with notable deviations in individual sectors and countries. In theory, the compared case of a constant average market share is a edge case of the model, and thus the coefficient of determination cannot be negative[59]. However, restricted parameters may cause negative R^2 in small sectors with very volatile behaviour. The authors decided to investigate the cases with R^2 below 0.3 (marked bold and darker background in Table 5.2), finding[60] that there are three major reasons for a low explanatory value:

59 A negative coefficient of determination R^2 would indicate that the model solution has a higher sum of squared errors than the case of a constant average market share. However, this average market share is also inside the solution space of the model. Therefore, when optimizing towards a high R^2, the model will at least have an R^2 of zero.

60 Values on the total energy demand in (i) to (iii) are taken from Eurostat (*2017*).

(i) Sectors with a small absolute energy demand and/or leaps in it. Among those are:
   a. Paper and printing in Ireland (R^2:0.02); total energy demand was 1.24 PJ in 2004 but dropped to 0.2 PJ in 2012
   b. Iron and steel in Croatia (5 PJ in 1992, 0.5 PJ in 2012) and Slovenia (around 3 PJ)
   c. Chemical industry Czech Republic (energy demand halved in 2010 from 43 PJ to 22 PJ)

(ii) Sectors in which the compared case of constant average market shares already is a very good fit (i.e. no or little long-term trends exist):
   a. Chemical industry in Austria
   b. Engineering and other metal in Netherlands (>95 % natural gas)
   c. Iron and steel in Austria, France, Poland, Norway

(iii) Sectors with (probably[61]) statistical issues
   a. Other non-classified in Hungary (no data on light fuel oil use in 2011/12, considerable use before and after)
   b. Non-metallic mineral products in Slovakia (virtually no reported waste use between 2000 and 2012, before and after between 4 PJ and 8 PJ)

In Figure 5.4, selected combinations of sectors and countries are presented. They are compared qualitatively; Eurostat's (*2017*) energy balance (left column), constant average market shares in the given time period (middle column) and the model results (right column) from 1992 until 2013. The areas represent market shares of different energy carriers. The above-mentioned case (i) is illustrated for the paper and printing industry in Ireland: The total energy demand halved in 2005, probably due to the closure of a mill. This leads to disruptive market share changes in the energy balance. Due to the diffusion assumptions in the model, it does not follow these changes and consequently creates results close to the base case of constant average market shares. Additionally, historically not observed energy carriers enter the market. This is less likely to influence the results, the more energy demand the investigated sector represents. Case (ii) is illustrated with the sector "engineering and other metal" in Spain. While natural gas shows some movement, the overall energy carrier shares do not change drastically over the observed period. Thus, the average constant market share already is a good fit. Case (iii) is illustrated using the "other non-classified" industry in Hungary. In 2011, an increase in light fuel use can be observed, with discontinued use in 2013. The model does not follow this development. The other diagrams presented in Figure 5.5 show examples of favourable sectors (large energy demand, no disruptive changes during observed period, mix of several energy carriers): iron and steel in Germany, non-metallic minerals in France, chemical industry in The Netherlands.

To address all these cases and capture the long-term trend of the fuel mix in the EU28, countries with low absolute energy demand can be aggregated into groups. This necessarily sacrifices details on those countries (the aggregated parameters cannot be applied to individual countries) but yields more

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61 It can be assumed that reporting methodologies were changed in some instances, especially regarding biomass and waste.

robust parameters since the above mentioned issues impact the model fit much less. Considering the absolute energy demand, individual parameters for the seven biggest energy consumers France, Germany, Italy, The Netherlands, Poland, Spain and The United Kingdom are presented. The other 21 EU member states share aggregated parameters in the results presented here but can (given the mentioned limitations) be calculated individually as well. The parameters are available as supplementary data.

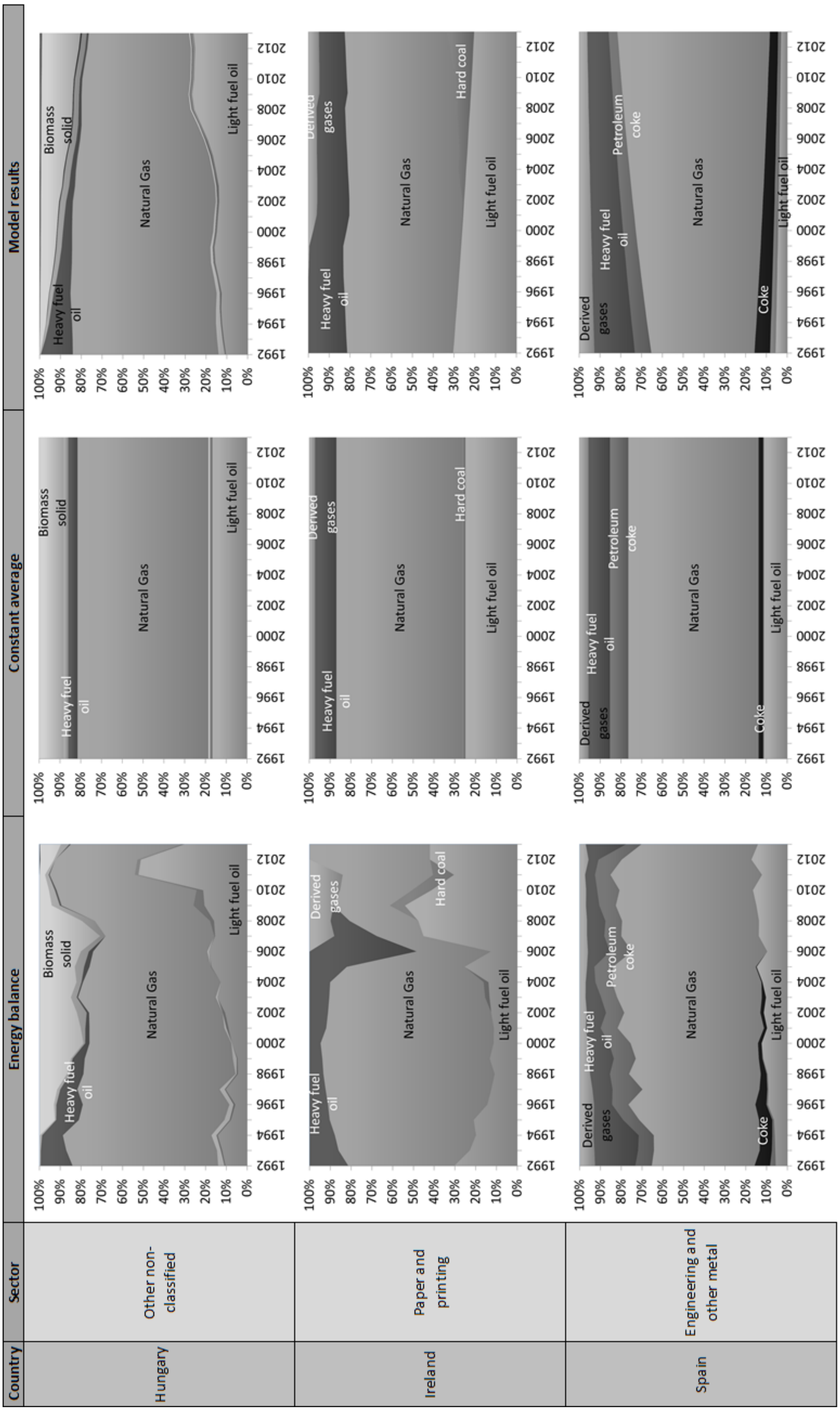

Figure 5.4: Comparison of energy balances (Eurostat 2017), constant average and model results for selected countries and subsectors

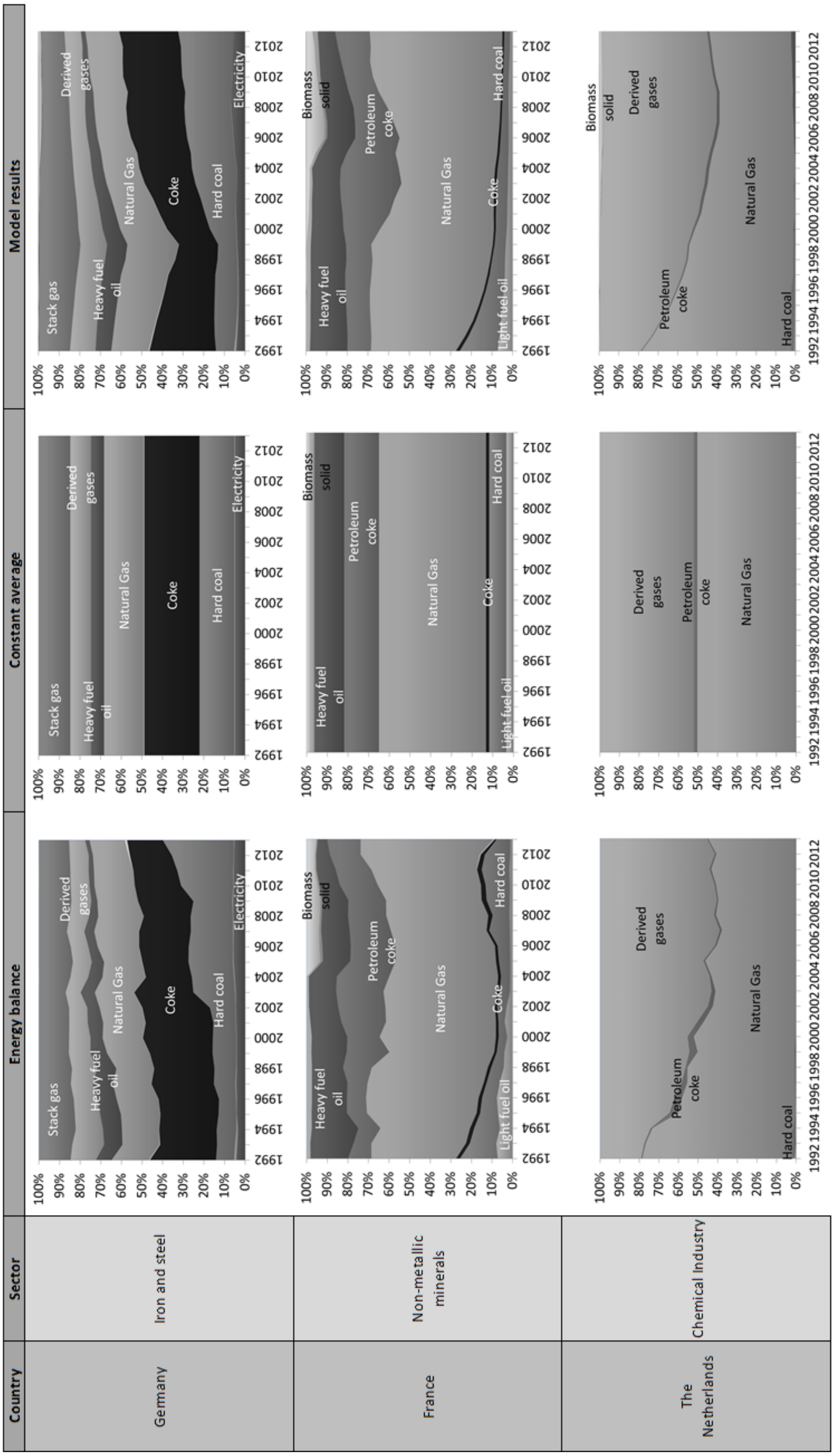

Figure 5.5: Comparison of energy balances (Eurostat 2017), constant average and model results for selected countries and subsectors

5.3.2 Model validation

The model validation is done similar to the model fit, with the following changes: Instead of using the full data series, only half (1992-2002) is used to fit the model. The model is applied to the other half (2002-2013). The results are compared against the constant market share of 2002, again using the coefficient of determination. Thus, the validation shows how much better the model describes the fuel share change during 2002 and 2013 compared to the assumption of constant fuel shares (Table 5.4). For this comparison, both models start with the actual market shares of 2002[62]. Note that next to the seven countries with the highest energy demand in scope, a group "others" is used. It comprises the 23 smallest consumers, which make up for around 32% of the energy demand in scope.

Table 5.4: Coefficients of determination (R^2) for the full model compared to constant energy carrier market shares (2002-2013)

Country	Chemical industry	Engineering and other metal	Food, drink and tobacco	Iron and steel	Non-ferrous metals	Non-metallic mineral products	Other non-classified	Paper and printing	Refineries	Average
France	0.66	0.63	0.74	0.41	0.83	0.13	0.47	0.66	0.64	**0.57**
Germany	0.71	0.78	0.96	0.68	0.67	0.19	0.23	0.5	-0.13	**0.51**
Italy	0.39	0.73	0.11	0.78	0.26	0.83	0.54	0.71	0.59	**0.55**
The Netherlands	0.65	0.28	0.27	0.51	-0.12	0.86	0.8	-0.02	0.5	**0.41**
Others	0.57	-0.19	0.47	0.61	0.49	0.7	0.17	0.76	0.41	**0.44**
Poland	0.5	0.79	0.91	0.62	0.53	0.79	-0.43	0.69	0.52	**0.55**
Spain	0.95	0.48	0.76	0.32	0.71	0.66	0.9	-0.52	0.39	**0.52**
The United Kingdom	0.84	0.04	0.9	0.65	0.5	-3.31	0.34	0.69	-0.1	**0.06**
Average	**0.66**	**0.44**	**0.64**	**0.57**	**0.48**	**0.11**	**0.38**	**0.43**	**0.35**	**0.45**

As can be expected, the overall R^2 is lower than the one observed when the whole time series is used as model fit. Additionally, some sectors show negative R^2. These are caused by disruptive changes similar to those already shown in Figure 5.4 (Ireland, Hungary). If they happen during the model fit, the respective energy carrier is overestimated in the second half. If this development stops or reverts, the assumption of a constant market share can yield better results (e.g. United Kingdom, non-metallic minerals (-3.31); Poland, other non-classified (-0.43)). The low R^2 (-0.12) for The Netherlands, non-

62 I.e. errors accumulated during model calibration (1992-2002) are removed.

ferrous metals can be considered less grave, as the total deviation of the modelled from the historic market shares sums to only 6%[63].

5.3.3 Country and Subsector Comparison

Whether an energy carrier is favoured or avoided in a given country and subsector can be described qualitatively by comparing the two energy carrier-related parameters price sensitivity α and structural factors γ. An energy carrier has easy market access when the price is perceived as low and γ is high. High values of α increase the impact of price changes in both directions. The lower α is, the more stable a sector's market shares will be. As price relations change over time, only a qualitative analysis is presented. Table 5.5 and Table 5.6 compare parameters of selected energy carriers by country and subsector. In both tables, the parameters are averaged over the respective not displayed dimension (country or subsector).

For biomass, in general a high price sensitivity (α) and low structural factors (γ) can be observed. The opposite is true for natural gas. The patterns for coke and hard coal resemble each other on the subsectoral level, highlighting that they are mainly used in the iron and steel industry (blast furnace). Coke however shows a slightly lower price sensitivity and higher structural advantages. Both coke and hard coal have a price lower than average and high values of price sensitivity α which increases the perceived utility. On the country level, hard coal stands out in Poland with an extraordinary high structural factors γ, compared to the other countries. Electricity is a special case, as it is not used in many subsectors; the resulting parameters are therefore not as robust as for other energy carriers; low price sensitivity α and high structural factors γ are present in all countries and subsectors.

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63 However, the assumption of a constant market share would be a better choice as this particular market shows high dominance of natural gas (>85%) and no trend to change.

Table 5.5: Parameter comparison of selected energy carriers by subsector (higher values marked darker)

Energy carrier	Country averages	Chemical industry	Engineering and other metal	Food, drink and tobacco	Iron and steel	Non-ferrous metals	Non-metallic mineral products	Other non-classified	Paper and printing
Biomass	Alpha	7.63	7.88	6.88	6.50	7.88	7.88	4.63	4.78
	Gamma	-	0.50	1.13	0.38	0.19	0.24	5.02	4.67
Coke	Alpha	3.01	1.68	3.09	3.88	1.10	1.02	2.46	2.67
	Gamma	0.57	1.31	1.67	8.29	3.03	1.26	0.78	0.43
Hard coal	Alpha	1.65	1.53	2.13	4.80	1.68	1.78	2.69	1.91
	Gamma	3.38	2.20	4.23	5.77	2.49	2.29	2.63	3.41
Natural gas	Alpha	2.47	1.18	2.77	2.37	2.11	2.64	3.60	1.96
	Gamma	7.08	9.19	8.85	8.67	9.34	5.15	8.99	7.85
Electricity	Alpha	1.00	1.00	1.00	1.08	1.09	0.25	1.53	1.00
	Gamma	5.38	6.56	6.63	7.88	7.63	2.40	5.75	5.94

Table 5.6: Parameter comparison of selected energy carriers by country (higher values marked darker)

Energy carrier	Subsector averages	Germany	France	Italy	The Netherlands	Poland	Spain	The United Kingdom	Other
Biomass	Alpha	7.63	7.06	7.52	3.89	7.35	6.15	8.63	5.81
	Gamma	2.09	2.31	0.66	0.16	1.83	1.28	0.98	2.82
Coke	Alpha	1.50	1.75	2.79	1.38	5.51	2.13	1.80	2.06
	Gamma	2.46	2.46	1.47	1.33	2.04	2.15	2.17	3.26
Hard coal	Alpha	2.18	2.97	2.72	1.63	1.44	1.98	3.61	1.64
	Gamma	2.74	2.83	1.05	1.57	8.06	1.15	3.68	5.31
Natural gas	Alpha	2.32	2.73	2.63	2.10	1.00	1.27	3.27	3.78
	Gamma	8.98	8.09	7.85	7.96	7.96	7.89	7.21	9.17
Electricity	Alpha	0.89	1.42	0.89	1.04	0.96	0.98	0.89	0.89
	Gamma	6.69	4.82	6.98	4.96	5.85	6.44	6.20	6.23

5.4 Discussion and conclusion

This paper proposes a discrete choice decision model based on existing knowledge about inter-fuel substitution and industrial high temperature energy demand. It is interpreted according to relevant characteristics of the industrial sector. Among those are an assumed high rationality; heterogeneity, undisclosed (i.e. unknown to the observer) information; inertia through capital stock turnover and inherent preference for some technologies via existing infrastructure and technical restrictions. The model parameters are estimated using a least-squares-fit to historical data of energy carrier prices and market share from 1992-2015 for countries in the EU28. Several aspects of the model construction require special attention and discussion: the intended technological explicitness, uncertainty considerations of the used data and the quality of the estimated model parameters.

5.4.1 Technological explicitness

In order to include information special to high temperature energy demand, (e.g. importance of the fuels caloric value, flue gas treatment and requirements of individual processes), closer investigation of the most relevant processes is necessary. This includes technological limitations both on the process- and fuel-side. Prominent examples of this are coke use in blast furnaces and temperature dependence of fuel suitability (*Beckmann et al. 2003, Davies et al. 2001)*, e.g. waste and biomass use in clinker production. This can be translated into limits to price sensitivity, which creates a supplementary choice probability for the specified energy carrier in case the calculated choice probability is lower than the given threshold. It reflects the need to use a certain energy carrier regardless of the price, but because of their special, process related properties. There are also other limitations to consider, e.g. exhaust gas-cleaning temperature, fuel composition. These considerations must be included on the process-level and can influence the fuel-switch potential substantially.

Additionally, the decision to switch to another energy carrier does not only depend on fuel prices but also on the costs related to process changes (e.g. new burner, fuel storage, other infrastructure). These costs depend at least on the process and both the old and new energy carrier, additionally the plant level gains importance. In the model presented here, they are considered in the logit parameters in an implicit form. Activity shifts to other processes (e.g. towards a combination of direct-reduced iron and electric arc furnaces (DRI/EAF) in the steel industry (*Hu, Zhang 2017*) are not included in the fuel switch model. In terms of technological explicitness, this is unsatisfying. However, the model offers the opportunity to include these dimensions exogenously during scenario definition.

5.4.2 Uncertainty considerations

The model presented in this paper relies on statistical data on energy demand and prices and technological data from literature. The intended application of the model in a scenario analysis implies inert uncertainty of the results, as they strongly depend on estimations of future developments (industrial activity, fuel prices, policy measures, technological development...). Considering these elements under deep uncertainty, the uncertainty connected with the used statistical and technological data is assumed to be relatively low. Main concerns regarding the used energy balance (*Eurostat 2017*) are the lack of quantifiable uncertainty statements and the possible differences in data quality among countries, as the data is gathered by national institutions. Shortcomings in the available energy balances can have a considerable influence on the model fit, especially the introduction of new energy carrier aggregations during the investigated timeframe. The impact can be mitigated by careful manual calibration[64] and longer time series. Despite several occurrences of inconsistent or implausible statistical data (e.g. Ireland, paper and printing in Figure 5.4) the data basis on energy demand is considered to be the best available for the given scope.

It applies to many efforts regarding industrial energy demand that data availability varies not only among countries but also among sectors, which impedes a detailed analysis. Particularly the lack of time series on the temperature level of the energy demand and its respective fuel use increases the uncertainty of projections. As of today, it must be assumed that the results given in Naegler et al. (*2015)* and Rehfeldt et al. (*2017)* on temperature distribution of the European industry in 2012 are representable for the industrial structure and therefore have not changed too much over the last twenty years. This is, however, far from certain. The approach to adapt revealed preference parameters taken from *total* industrial energy demand to *high temperature* industrial energy demand is thus an approximation. That data availability poses a major challenge especially in the industry sector and on new technologies for both energy efficiency and structural change has already been acknowledged by researchers dealing with bottom-up models, recently Fais et al. (*2016*). This concerns historic data on demand and costs on a disaggregated level (or even on the top-level of energy balances in some countries) just as much as assumptions on future technologic and economic development. The technological and economic situation can vary on the plant level, while the model works on both the process and subsector level. The conclusions of this paper are therefore not applicable to individual plants but to subsectors and countries.

No price differentiation is made among sectors or company size, as historic data are not available at this level of detail. This can be relevant for natural gas and especially electricity, while world market prices can be assumed adequate for hard coal. Some energy carriers like derived gases are not traded at all on free markets but rather used on-site for power generation or sold directly with no or little transparent pricing. The only clues available on the price in these cases are assumptions on what traded energy carriers might be replaced or replaceable by them. Existing data gaps are filled via interpolation or analogies with other countries whose development is similar in the observable timeframe. These data imperfections raise concern about the reliability of price-related model responses, especially how much the price model input relates to the price actually perceived by market participants in the individual processes and sectors. As the model works on price differences rather

[64] In this regard, manual calibration refers to the adjustment of parameters or input data, where errors or inconsistencies are assumed (see examples given in 3.1).If, for example, in Figure 5.4, the spike of fuel oil in 2006 would safely be identified as statistical issue and ignored, the overall result of this country/subsector would improve. However, this detail of analysis is hard to achieve when a large number of countries and subsectors are investigated.

than absolute prices, though, it can be assumed that the price paths represent the real price signals in a qualitative way.

The parameters derived in this paper are based on revealed preferences. Thus, their explanatory value is limited to observed behaviour. This limitation is most relevant for energy carriers that have not been present in the industrial sector for a long time or are seldom used. While, for example, natural gas is used in all sectors and countries, biomass is mainly used in the paper industry and to some extent in engineering, food industries, non-metallic minerals and other industries (as categorized in Eurostat (*2017*). Generally, the parameters are assumed to be less certain the less the respective energy carrier has been observed in the past[65]. Additionally, there is the elemental critique on all projections; they rather extended the past than describe the future. This has some foundation in general, but in case of the model presented here, it is of special concern. As the parameters are defined to be constant over time, so are all factors which influence fuel switch that are not explicitly included in the model. While some important policy measures can be included as variables (taxes, levies, subsidies, CO_2-pricing), the change of not monetarized or not monetizable effects are neglected or so far only treated implicitly. This includes several dimensions identified as being relevant in the context of fuel choice (e.g. health (*IPCC 2014*) and security of supply (*European Commission 2014a, b)*). Thus, the model assumes that decisions made in the past will be made again in the future (given the same circumstances). This is a limitation of the model. It seems plausible that decision patterns change over time, for example due to policy influence. It is possible to integrate dynamically changing preferences into the model, these can be used in sensitivity analyses and scenario exercises (e.g., what would happen if biomass were perceived like coal?).

5.4.3 Parameter discussion

The parameters derived from the model fit must have an equivalent in reality in order to be of use in a scenario analysis. They are supposed to address different observations: α accounts for properties of the individual energy carriers (e.g. stability of combustion, phase, heating value, flue gas composition). As an aggregate, it describes how valuable the energy carrier is perceived in the respective industry and their typical applications. This influences how relevant price differences (both between alternatives and intertemporal) are when evaluating the utility of the energy carrier. Markets that react strongly to price changes will show high values of the price sensitivity α[66]. The structural factor γ addresses the historic prevalence of energy carriers. It influences the perceived utility independently of the price to account e.g. for existing infrastructure, delivery contracts and long-term technology choice. Price sensitivity α and the structural factor γ cannot always be separated, as for

65 For example, if biomass is not observed in a given subsector, the respective value for γ is likely to be very low. However, whether it is 1 or 2 is irrelevant for the model, as long as it is low enough to generate a low utility. Due to the sigmoid shape of the logit-formulation, very high and very low utilities are much more robust to parameter variations, which in turn means that these parameters derived from the calibration are less certain.

66 And/or high values of ε, as they are multiplied. The combination of all parameters has to be considered.

example the choice for a furnace type or burner can influence both. The differentiation is easiest for actions that are related to infrastructure, e.g., investments in natural gas access or coal storage should increase the respective structural factor γ but have no influence on the price sensitivity α. ε describes the market homogeneity and therefore transparency. It is high in subsectors with uniform products or process requirements. This parameter also includes soft factors like available information on available technologies and fuels or available capital. Therefore, the market homogeneity ε is a measurement for the degree to which the objectively best solution (according to the model) is actually used[67]. Finally, the diffusion factor δ describes the inertia of the system. It modifies the speed, with which decisions are implemented. It relates to capital stock turnover and modernization cycles, including short-term (e.g. in multi-fuel burners), medium-term (e.g. modernization of a plant) and long-term fuel switch (e.g. new plants). Subsectors with long investment cycles show lower values (i.e. a lower diffusion speed).

The solution space for the parameters has been restricted. Most of the restrictions are introduced in order to reduce the impact of leaps in historic market share time series that cannot be explained via market-related diffusion and technological considerations.

The restriction of the price sensitivity α being smaller than -1 is associated to some occurrences of simultaneously rising natural gas prices (both relative and absolute) and market shares in the investigated time series. The resulting price sensitivity would therefore be positive[68]. As this contradicts basic economic theories, it is assumed that unknown factors have influenced the development in this time span. Possible influences are errors or lags in the time series for energy demand and prices, capacity-changes that were planned unrelated to fuel prices or a lag between investment decision and realization. Although this observation hints at model imperfections, it is not uncommon (e.g. *Jones 1995*). Especially for electricity and, more important, natural gas, the impact of individual delivery contracts (e.g. with different pricing structures than assumed) cannot be modelled. However, for projections, the assumption of positive price sensitivities would be unsuitable (and inconsistent with the majority of the sectors and countries). It has therefore been assumed that for these special occurrences, price sensitivity is very low, resulting in the need for substantial price shocks to influence the market share.

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67 In model terms, this can be explained by the sigmoid logit-function. When the utility-values are multiplied with a constant factor, the highest utility profits most and increases its market share. Thus, a high market homogeneity ε increases the differentiation among alternatives.

68 As can be seen in Labandeira et al. (2017), price elasticities can be assumed to be negative; though examples of positive values exist in some studies. Although the price sensitivity α derived here is not a price sensitivity, it behaves as one regarding its sign.

The diffusion factor δ is constrained to values between 0.1 and 1 because a slower diffusion would imply extremely long stock turnover cycles and a lack of short-term fuel-switch options[69]. At the same time, a diffusion factor higher than 1 could potentially destabilize the market share calculation. The restrictions on this parameter and its interpretation require additional research, but model calibrations without restrictions on δ showed values between 0.04 and 0.27. The market homogeneity *ε* is limited to be smaller than 10 to reduce the impact of market share leaps in the historic data. These occur in small sectors that are heavily influenced when plants start or cease operations. In accordance with the theoretical background (long-term fuel-switch), these events are not included in the model. During model calibration, it has been observed that a balanced definition of price sensitivity α and structural factor γ is very important to create a good model fit to the historical data while retaining price sensitivity for scenario exercises. If this balance is not kept, the model tends towards keeping the status quo (high weight on structural factor γ). Critically reviewing the parameters proposed so far, one could argue that the potential for a substantial fuel switch is limited. The calculation example shows that the price component of the utility calculation makes up for a limited share of the total utility value. Although the logit approach is sensitive to small changes and thus price changes can influence the market share considerably, fundamental shifts (e.g. biomass asserting dominance over natural gas in the non-metallic minerals) are unlikely. While this limitation reflects observed behaviour, it must be made transparent in a scenario analysis. In particular, in transformation scenarios, it must be kept in mind that the parameters reflect past preferences that can change in the future.

Lastly, the applied methodology of *revealed preference* parameters (i.e. preferences observed in the past) performs poorly when trying to evaluate the utility values of energy carriers that were not (or only to a little extent) present in the market during the observed time frame. Potentials tend to be greatly underestimated when the mostly hesitant adoption of new energy carriers is extrapolated into the future. This most prominently applies to the several forms of biomass-based energy and electricity-use for heating. Especially in the context of decarbonisation-scenarios, this is unfortunate as biomass often plays a major role. At the same time, it must be conceded that the methodology to derive model parameters from top-down statistical data does not work well for small sectors (i.e. small number of market participants and low absolute energy demand), since disturbances that are not included in the model (e.g. start or cease of operations) greatly impact market shares of energy carriers. It seems to be beneficial to complement the revealed preferences proposed in this paper with stated preferences that can include future-oriented and hypothetical constellations.

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69 While technical lifetimes of installations of 40 years and more are plausible, maintenance cycles and major revisions offer the opportunity of adjusting the energy use in shorter periods. A δ of 0.15 relates to diffusion times of 7 to 12 years.

5.4.4 Further work

As Rivers et al. *(2003)* and McCollum et al. *(2016)* point out, heterogeneity among the investigated groups is important for decision models. The model can be improved in this dimension by considering individual processes rather than sectors (e.g. “primary copper production” instead of “non-ferrous metals”) already during the economic model part. This is mainly hindered by data availability regarding individual processes especially regarding economic data (i.e. energy carrier prices) and more detailed energy balances. Ultimatively, the plant level must be considered to really capture the heterogenous industrial structure. Further work on the model must include the quantitative or qualitative support of the parameters derived in this paper. While the model fit strongly suggests that they are suitable to describe the past development adequately, the application in a scenario analysis demands credible argumentation regarding their consistency and plausibility beyond reproducing the past. This requires the implementation of stakeholder expectations and expert knowledge e.g. in the form of stated preferences. To this end, a survey and a series of expert interviews are currently in progress. Additionally, the technical limitations of processes whose implementation is an important benefit of the model should be described in detail.

5.4.5 Conclusion

A decision model based on the discrete choice theory that includes market- and technological-driven utility considerations is presented. It describes the energy carrier choice as a combination of consumption preferences and price signals. Inertia of technology stock is modelled using a potential-difference diffusion function. The decision model is included in the bottom-up energy demand simulation model FORECAST (*2016*) by focusing on sectoral heterogeneity and its impact on the energy carrier and the technology choice. Energy balances and historic price data are used to determine revealed preferences of market participants on the sector level. Long-term trends of energy use are captured with estimated parameters, while short-term effects are neglected or smoothed. This behaviour is favourable for scenario analysis and projections, since they usually aim at robust trends and thus use continuous developments of input data (e.g. energy price paths). Therefore, the presented methodology for integration in a bottom-up model and the estimated parameters are well suited for this application. Limitations of the approach (e.g. data requirements) are discussed.

The results show considerable differences between energy carriers and subsectors. They highlight the different market positions of biomass as a (relative) newcomer and natural gas as an established solution in virtually all subsectors and applications: Price advantages (e.g. CO_2-pricing) are very influential for biomass market penetration and strongly incentivize a fuel switch. At the same time, biomass has to outweigh several benefits of natural gas (e.g. existing infrastructure for transport and use). The dominant role of coal and coke in the steel industry is underlined by the high γ found, especially in countries that rely on blast furnace operations (Poland, United Kingdom, Germany), while Italy as a traditional secondary steel producer shows lower γ for coal.

Due to relatively high prices for electricity (e.g. in Germany 2013 40 €/GJ compared to an average of all energy carriers of 13 €/GJ), a considerable price reduction is needed to increase its market share. In particular, the price changes observed in the investigated period were not sufficient to have an important impact on the market share. Except for the subsector non-metallic mineral products, high structural values (γ) for electricity can be observed. They point at applications, in which electricity is used despite its high price (e.g. electric arc furnaces in iron and steel and the chemical industry, production of aluminium in non-ferrous metals). In the context of process heat electrification though, it is questionable whether the derived parameters are able to describe future developments, which are potentially very dynamic.

The validation of the model shows that it yields better results than the immediate assumption of constant market shares in most cases. An average R^2 of 0.45 can be observed during the modelled timeframe (2002-2013) after a calibration period (1992-2002). Coefficients of determination as high as 0.96 can be observed in individual subsectors; on the other hand, negative R^2 are possible in extreme cases. Overall, the model excels at capturing long-term trends in inter-fuel substitution while it is negatively affected by highly dynamic markets and disruptive changes.

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6 Fuel switch as an option for medium-term emission reduction: A model-based analysis of reactions to price-signals and regulatory action in the case of the German industry[70]

Abstract

The German federal government set a GHG-emission reduction target for the German industry, aiming for a 49%-51% reduction by 2030, compared to 1990. Fuel switch towards electricity and biomass is potentially an important measure to meet the target. In this article, we investigate the potential contribution of fuel switch by applying economic incentives and regulatory measures in a bottom-up simulation model. The policy instruments of CO_2-price and technology-specific subsidies are applied in varying intensities. In addition, a ban on new fossil-based heat systems and accelerated stock exchange are simulated as regulatory measures. Results show that fuel switch and energy efficiency combined may, with considerable economic pressure (up to 300 €/t_{CO2} in 2030) and financial support for electricity-based process heating achieve emission reductions of up to 50% by 2030 compared to 1990, reaching the sectoral goal for industry.

We observe that both a CO_2 price and investment grants for electric process heating equipment are not effective to incentivise a sufficient market entry of electric heating by 2030. Introducing a CO_2 price mainly results in a high effect on biomass use, while the economic gap between natural gas and electricity is not closed sufficiently. Increased replacement of steam generation systems is an effective and necessary lever until 2030. Policies should therefore focus on both incentivizing and regulating the stock exchange of process heat and steam generation towards less emission-intensive systems. Reaching the German sectoral target for industry increases the modelled system costs by 20% compared to a case without additional policies. Adding regulatory measures such as a ban on new fossil-based installations reduces the system cost increase to 15%.

To achieve long-term CO_2-neutrality, incentives for fuel switching are not sufficient, because important emission sources cannot be addressed by fuel switch to electricity or biomass. Therefore, the deployment of innovative industrial processes has a key role after 2030 or, if possible, earlier.

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6.1 Introduction

In its Climate Action Plan 2050, the German federal government defined sectoral goals for greenhouse gas (GHG) emission reduction [1]. These follow the national goals of, prior to net-neutrality in 2050, a reduction by 40 % until 2020 and by 55 % until 2030, compared to 1990. It is currently assumed that the 2020 target will not be achieved in time [2]. Therefore, increased attention is put on the 2030-target and the steps that need to be taken to achieve it.

The German Federal Government's proposal for the introduction of a CO_2-price focusing the sectors not covered by the European Emission Trading System (non-ETS) and thus under the Effort Sharing Decision (ESD) foresees a price of 10 €/t_{CO2} in 2021, 35 €/t_{CO2} in 2025 and a capped maximum price of 60€/t_{CO2} afterwards. Scenarios published in the past years assume higher CO_2 prices in scenarios with GHG-reductions of 95% until 2050, for example 200 €/t_{CO2} in 2050 in [3]. The EU Energy Roadmap 2050 [4] assumes a range of 234 €/t_{CO2} and 310 €/t_{CO2}, depending on, among others, the availability of breakthrough technologies. This resembles the costs incurred by GHG-emissions assumed by [5] between 180 €/t_{CO2} in 2016 and 240 €/t_{CO2} in 2050. Pathways aiming for 80% reduction[71] on the other hand, include CO_2-prices in a range not far off the now proposed pricing path [6,7][72]. Additional measures in the proposed legislation include a ban on new oil-based heating systems in the residential sector starting 2026.

In 2015, Germany reported 907 $Mt_{CO2\text{-}eq.}$ GHG-emissions under the UNFCC framework [8,9].The manufacturing industry accounted for 185 $Mt_{CO2\text{-}eq.}$ (about 20 %)[73]. Major contributions to these emissions are the use of fossil fuels for process heat and self-produced electricity ('energy-related') and chemical reactions during production ('process-related'). Indirect emissions from externally generated electricity and heat are excluded from the industry sector and balanced in the energy sector. Until 2030, the industry sector target of the Climate Action Plan 2050 requires a reduction between 49 % and 51 % compared to 1990. In absolute terms, this equals a remaining annual emission between 140 $Mt_{CO2\text{-}eq}$ and 143 $Mt_{CO2\text{-}eq.}$ (1990: 283 $Mt_{CO2\text{-}eq.}$) in 2030. Until 2014, the yearly emissions had already been reduced to 181 $Mt_{CO2\text{-}eq.}$ This was achieved by increased energy efficiency [10] and fuel switch away from coal and oil, often to natural gas and electricity. Additionally, in the wake of the German Reunification, large parts of the former East Germany industry were dismantled, which substantially contributed to the observed emission reductions.

Despite the already implemented fuel switch from oil and coal to gas, considerable additional potentials exist. These include the electrification of steam generation, the use of biomass as reducing

71 This used to be the lower end of the target range (between 80% and 95%), but has been replaced by the term 'net-neutrality', commonly quantified as ~95 % reduction in subsequent plans.

72 These did often merely included the established EU ETS. CO2-pricing in the non-ETS sectors were, in the past, considered politically unlikely.

73 Excluding LULUCF.

agent or feedstock as well as increased electrification in specific industrial processes (e.g. glass melting). While fossil fuels are not endless, estimates on their reserves support the idea that a climate change mitigation must happen demand-driven, as the supply would "*still lead to a significant near-term growth in carbon emissions by the middle of the century*" [11]. Next to carbon capture and storage and breakthrough technologies, fuel switch and in particular electrification of important industrial processes are discussed as means to change the demand structure, reaching their full potential only in an integrated approach [13]. To support deep decarbonisation in the long-term, sectoral approaches are useful to account for the highly individual challenges of industrial activities [16]. In addition, the importance of carefully designed policy packages, including carbon pricing, R&D support for emerging technologies as well as policy support for near-commercial technologies and the guiding role of public institutions is stressed [18]. Important fuel switch options are available today and can be introduced into the market immediately. They are thus capable to support the road to 2030 targets.

Several individual measures for fuel switch are under investigation. Steam generation, important especially for the sectors paper, chemicals and food processing, are considered a promising technology field for increased use of biomass [12] and electricity [14]. Moreover, fuel switch potentials are present in glass production [15], furnaces in the chemical industry [17], refineries [25] and non-metallic minerals [19]. In the steel industry, the use of biomass (replacing pulverized coal injection and enhancing coke making [20,21]) and electricity (in electric arc furnaces, [22]) are discussed. Based on the required effort, three categories of fuel switch can be identified: First, gradual fuel switch in existing installations, e.g. by co-firing of biogenic material in clinker furnaces. Second, fuel switch in new installations but within the currently established production processes, e.g. electric instead of natural gas-fired boilers. Third, the adoption of new production processes, e.g. replacement of blast furnaces with natural gas- or hydrogen-based direct reduction [23]. Considering the limited timeframe, only the former two categories are investigated here.

Estimates of the combined theoretical potential for fuel switching [24] in the EU28 industry suggest they might even suffice to match the stricter goals required by pathways compatible with 1.5 °C global warming laid out by the IPCC [26]. However, these estimates consider only the industries participating in emission trading in the EU28 (2015: 420 $Mt_{CO2\text{-}eq.}$) and do not take into account economic limitations, system inertia (e.g. investment cycles) and behavioural aspects of investment decisions. It is therefore necessary to conduct closer investigations of the measures discussed and assess their economic conditions to transfer the theoretical into a practical potential. For short-term fuel price changes, especially when policy-induced, it was found that supporting the transition to other fuels by supplying affordable and reliable alternatives is critical to facilitate fuel switch [27].

This article applies the energy-system model FORECAST to estimate economic and behavioural fuel switch potentials in the context of alternative regulatory frameworks. FORECAST features price sensitivity of energy carrier choice, technologies competing based on their economic and technological attractiveness and consumption choice preferences. It is thus well suited to investigate the economic requirements and opportunities of fuel switch. In this publication, we design four scenarios: First, a 'Base' scenario with price signals of different intensities but no further measures. Second an 'Investment' scenario with subsidies to investments. Third, the 'Replacement' scenario, in which the exchange of installations is increased. Fourth, the 'Regulation' scenario, which adds a ban on fossil steam generation. Investigated parameters to influence economic attractiveness include technology-specific subsidies for operational ('Base', 'Replacement' and 'Regulation') or capital expenses ('Investment'), CO_2-prices (in ETS and non-ETS, all scenarios) and the technology stock turnover of steam generation equipment and furnaces ('Replacement' and 'Regulation'). Regulatory measures focus steam generation systems and force early replacement of emission-intensive systems as well as a ban on new fossil installations after 2025 ('Regulation'). The role of energy efficiency is not investigated separately but included in all scenarios. CO_2-price sensitivities are presented for each scenario resulting in 192 model runs. The GHG-emission reduction potentials are put in relation to the system costs. We finish with an overview of the remaining emissions and challenges beyond fuel switch.

This article focuses on Germany. As shown in earlier publications, the profiles of process heat use in Germany and the EU28 are similar [28]. Conclusions drawn from this article are thus of interest for other countries with similar industrial structures and the EU28 as a whole, while national particularities like energy prices etc. of course need to be taken into account.

6.2 Methodology

The applied methodology follows three steps: First, we calibrate the simulation model FORECAST to the official emission balances in order to allow precise conclusions for the 2030 target. This includes allocation of process- and energy-related emissions and closing of gaps between the used statistics. Then we define policy measures, emission targets and framework data and compose four scenarios. Last, parameter variations are applied to the scenarios to investigate the impact of different subsidy- and CO_2-price levels on GHG-emission, heat generation costs and system costs.

6.2.1 Emission reduction targets

The German climate targets for the industry sector in 2030 include a reduction of GHG-emissions between 49 % and 51 % compared to 1990 [1]. For 1990, the CRF-tables report 279 $Mt_{CO2\text{-}eq.}$ within the scope laid out in Table 6.2[74]. In absolute terms, the target for 2030 is therefore 140-143 $Mt_{CO2\text{-}eq.}$.Two third (94 $Mt_{CO2\text{-}eq.}$) of the necessary reduction have been achieved until 2010 (Table 6.1). The European Union as a whole has set emission reduction targets of 40% compared to 1990 levels; 43% in the sectors currently under the ETS and 30% in non-ETS [37]. Paris-compatible targets are more ambitious: The pathways compatible with 1.5 °C global warming reported by the IPCC [26] require overall reductions of GHG emissions by 45 % until 2030, compared to 2010-levels[75]. For simplicity, we assume that this reduction is made equally in all sectors and countries. Thus, the German industry would be required to reduce emissions to 102 $Mt_{CO2\text{-}eq.}$ until 2030 to stay on a 1.5°C pathway. This would equal a reduction by 64% with a 1990-basis, of which 34% has been achieved until 2015.

Table 6.1: Emission reduction targets considered for this analysis

Industry		*1990*	*2010*	*2015*	*2030*
Sectoral target Germany	Absolute Emissions [$Mt_{CO2\text{-}eq.}$]	279	185	185	<143
	Reduction (1990)	-	34 %	34 %	>49 %
IPCC 1.5°C pathway (broken down to German industry)	Absolute Emissions [$Mt_{CO2\text{-}eq.}$]	279	185	185	102
	Reduction (2010)	-	-	0%	45 %
	Reduction (1990)			34%	64%

6.2.2 Model calibration to official emissions reporting

The German sectoral GHG-reduction goal for the industry is measured via the national inventory report (NIR) [9]. It is based on common report format tables (CRF) [8]. In their 2019 version, the

74 These values differ slightly from those used in [1] due to updates in subsequent publications. We assume that the relative targets are kept constant and base the analysis on the latest available data [8,9]. This difference does not affect the 2030 goal substantially.

75 Between 39 % and 51 % (interquartile range) in the illustrative P2-scenario, Figure SPM.3B. Thus, the virtual reduction goal given in Table 6.1 for a 1.5°C pathway may lie between 91 Mt and 113 Mt. Additional uncertainties, especially on the globally available carbon budget, apply.

CRF-tables report 185 $Mt_{CO2\text{-}eq.}$ of emissions for the industry sector (2015), including energy- and process-related emissions (Table 6.2). Energy use accounted for 127 $Mt_{CO2\text{-}eq.}$ (with 493 TWh), while process emissions accounted for 58 $Mt_{CO2\text{-}eq.}$

The energy system model FORECAST does not cover the entire emissions laid out in the CRF tables. It follows the definition of final energy from the German and European energy balances. For example, emissions from product use and hydrofluorocarbons (HFC) are omitted from the model. Additionally, it applies different sectoral definitions, e.g. for steam generation. Where in FORECAST steam generation is balanced (according to Eurostat energy balance [29]) in the respective end use sectors, the CRF tables report those in the category 'Other'. This category thus accounts for approx. 70 % of the industries energy demand. In contrast to the European energy balances, the CRF tables include energy demand and emissions from electricity generation in industrial power stations. The interpretation of GHG-emissions according to CRF thus require interpretation in FORECAST.

For the purpose of this research, we assume that the emissions from electricity generation in industrial power stations follow the sector's emission paths. To compare the model outputs with climate targets, the results are calibrated to the CRF tables in the start year 2015. To this end, the following modifications to the model data are made (Table 6.2):

- Sub-sectoral differences are disregarded for the calibration, as they are obfuscated by steam generation and process emissions definition differences
- Total industry energy use and energy-related emissions are scaled to CRF values
- Process-related emissions not included in FORECAST (D-H in Table 6.2) are added as absolutes in 2015 (14.5 $Mt_{CO2\text{-}eq.}$)
- Emissions from coke and coal use in the steel industry are removed, as they are covered as energy related in FORECAST (13.1 $Mt_{CO2\text{-}eq.}$)
- The remaining process-related emission difference is scaled to CRF

Table 6.2: Difference in energy and emission balance between CRF (used to define 2030 targets) and FORECAST and resulting scaling factors (2015)

		CRF	*FORECAST*	*Difference*	*Method*	*Detail*
Emissions energy-related [kt]	**INDUSTRY**	**127.1**	**114.6**	**-12.5**	Scaling	Factor: 1.24
	a. Iron and steel	40.2	51.5	11.3		
	b. Non-ferrous metals	0.2	2.3	2.1		
	c. Chemicals	0.0	21.0	21.0		
	d. Pulp, paper and print	0.0	6.7	6.7		
	e. Food processing	0.2	7.7	7.5		
	f. Non-metallic minerals	13.3	14.7	1.4		
	g. Other	73.2	10.7	-62.5		
Emissions process-related [kt]	**INDUSTRY**	**57.7**	**31.1**	**-26.6**	Scaling	Factor: 0.92
	A. Mineral industry	19.5	20.0	0.5		
	B. Chemical industry	6.9	7.3	0.4		
	C. Metal industry	16.9	3.8	-13.1	Remove difference:	13.1 Mt
	D. Fuels and solvent use	2.1	0.0	-2.1		
	E. Electronics industry	0.0	0.0	0.0		
	F. Substitutes for ODS	11.3	0.0	-11.3	Add as constant to FORECAST	14.5 Mt
	G. Other product use	0.4	0.0	-0.4		
	H. Other	0.7	0.0	-0.7		
Energy [TWh]	**INDUSTRY**	**493.1**	**435.8**	**-57.2**	Scaling	Factor: 1.13
	a. Iron and steel	76.9	131.4	54.4		
	b. Non-ferrous metals	0.6	10.7	10.2		
	c. Chemicals	0.0	90.7	90.7		
	d. Pulp, paper and print	12.7	36.9	24.3		
	e. Food processing	0.5	35.9	35.4		
	f. Non-metallic minerals	55.4	62.9	7.5		
	g. Other	347.0	67.3	-279.7		

6.2.3 Approach to emission trading (EU ETS) and effort sharing decision (ESD)

The industry sector investigated in this publication is part of two mechanisms for emission reduction: The European Union Emissions Trading Scheme (EU ETS) is relevant for all energy-intensive subsectors, excluding only food processing and 'other' in Table 6.2[76] [30]. Of the 185 $Mt_{CO2\text{-}eq.}$ in the CRF tables, 98 $Mt_{CO2\text{-}eq.}$ (2015) are registered in the verified emissions [31]. Compared to the total amount of registered emissions of 465 $Mt_{CO2\text{-}eq.}$ (2015) in Germany, the industrial emissions in the EU ETS are small. The power sector dominates the EU ETS and thus the market price [32] up to a point where the electricity generation price in Germany alone is found to have a large and significant impact on the price of EU allowances [33]. The sectoral approach taken in this publication thus does not allow to model emission trading per se. The market price is strongly affected by emissions outside the system boundaries; to explicitly model trading requires representation of all participating sectors [34]. We thus select a reverse approach, in which an emission price is assumed and the reaction on that price signal observed. This allows assessing price sensitivities and reduction potentials in the industry sector.

In the subsectors affected by effort sharing, the national governments are responsible to ensure compatibility with European targets of 30% reduction until 2030 (compared to 2005, [35]). They are thus obliged to enact policies to facilitate emission reduction. For Germany, this coincides qualitatively with national targets and we investigate CO_2-pricing in the non-ETS sectors as a currently discussed policy instrument [36]. We assume that the national ETS included in the current proposal of the German Federal Government will be combined with the EU ETS. For both mechanisms, the same price path is assumed.

6.2.4 Model description

The FORECAST model is a bottom-up simulation model. It assumes a techno-economic point of view on individual technologies and industrial processes in the energy intensive industries. In addition, efforts have been undertaken to include behavioural aspects of energy use and investment decisions in the model. A detailed methodology description for the industry sector was published recently [38]. The general structure of the heating demand used in the model is summarized e.g. in [39]. Fuel switch itself is modelled in three distinct technology fields: steam generation, furnaces and space heating. Steam generation and space heating both share the methodological approach of stock models, in which the final and useful energy demand is covered by an existing technology stock. This stock is gradually replaced when installations reach the end of their lifetime [40]. Due to their different requirements (e.g. temperature level and capacity), process heat and space heat use a different set of technologies. Due to missing stock information, high temperature heat generation in industrial furnaces does not apply a stock model, but assumes replacement rates of installations based

[76] Parts of these subsectors are included based on the 20 MW capacity per installation threshold.

on historical replacement on a subsector level. All of the technology fields share the methodology to determine the technologies entering the market. In a discrete choice approach, the attractivity of technologies is determined by their total cost of ownership and behavioural preferences [41,42] that influence the perceived value of the technology.

6.2.5 Scenario definition

The analysis is carried out in four scenarios: Base, Investment, Replacement and Regulation (Table 6.3). The 'Base' scenario investigates the effect of CO_2-prices and operational costs-focused subsidies for electricity-based process heating (electric heat pumps, boilers and furnaces) on stock exchange, technology choice and GHG-emissions. These technologies are supported by a reduction of their heat generation costs, starting in 2026 and staying constant until 2030. The 'Investment'-scenario replaces support for operational expenses with investment support. Both scenarios do not assume a faster technology exchange than observed in the past. They also follow the observation, that the decision for new systems is often influenced by the old system's technology. Thus, only 50% of the replacing steam generation systems is based on economic considerations, the other half uses the same technology as before when the replacement decision occurs.

The 'Replacement'-scenario builds upon the 'Base'-scenario and adds early replacement of the technology stock. Fossil-based heating technologies are replaced when they reach 75% of their technical lifetime between 2025 and 2030. They may still be replaced by new fossil fuel technologies. An increased share of 75% of the technology choice is based on economic considerations.

The 'Regulation'-scenario builds upon the 'Replacement'-scenario and adds a fossil ban specifically for steam generation: After 2025, no newly built steam generation installations uses fossil- or fossil-derived fuels (natural gas, coal, oil, derived gases, non-renewable waste). This includes that all decisions for new steam generation systems (among the options available due to regulation) are based on economic considerations.

Table 6.3: Scenario structure

	Scenario	Base	Investment	Replacement	Regulation
Framework	Production activity	Depending on the product: Slow growth or stagnating			
	Energy carrier prices	Following historic trends			
Measures	CO2-price	25 EUR/t_{CO2} in 2020, linear growth to 50 EUR/t_{CO2} in 2030			
	Subsidies	Yes	No	Yes	Yes
	Investment support	No	100%	No	No
	Early replacement	No	No	75% of technical lifetime 2025-2030	75% of technical lifetime 2025-2030
	Fossil ban new installations	No	No	No	After 2025
	Rational choice	50%	50%	75%	75%-100%

All scenarios use the same assumptions about the industrial activity (Table 6.11) and energy carrier prices (Figure 6.1). No strong ambitions are assumed in terms of material efficiency or sufficiency and thus production grows slowly or remains constant until 2030. The scenarios also share behavioural preferences in steam generation and industrial furnaces[77]. The scenarios share a common CO_2-price, starting with 25 €/t_{CO2} in 2019 to 50 €/$t_{CO2\text{-}eq.}$ in 2030. The impact of higher levels of technology subsidies and higher prices on carbon emissions are further investigated in a parameter variation.

Electricity and natural gas prices for steam generation[78] consider price ranges depending on consumption according to Eurostat bands [43,44]. These create a range of 9 €ct/kWh to 19 €ct/kWh for electricity and 2 €ct/kWh to 5 €ct/kWh for natural gas in 2011, excluding recoverable taxes and levies. Companies with limited obligation to pay the levy according to the renewable energy law (EEG), reduced network tariffs and exemption from electricity tax may reach electricity prices between 5 €ct/kWh and 13 €ct/kWh ([43], excluding taxes and levies). In 2019, about 4% of the companies [45] were affected by the EEG-exemption. As these companies are not modelled explicitly but on a subsectoral level, their individual electricity price and thus the necessary subsidies to facilitate fuel switch may be overestimated.

77 Detailed in [41,42].

78 Electricity and natural gas use in industrial furnaces assume prices of the highest consumption band.

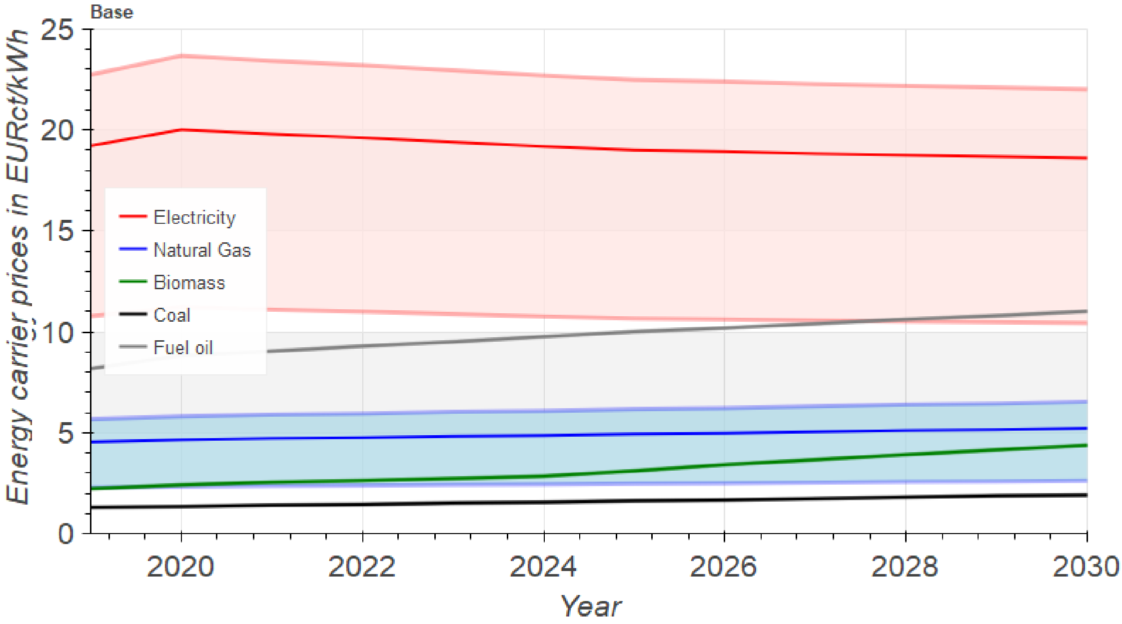

Figure 6.1: Energy carrier prices for all scenarios

In all scenarios, non-CO_2 emissions, in particular hydrofluorocarbons (HFC) are reduced by 70% until 2030, in line with the Roadmap 2050 of the European Union and respective legislation [46].

6.2.6 Parameter variation

In addition to the scenario differentiation, parameter variations for the scenarios are generated to investigate the impact of higher CO_2-prices and subsidies. A batch simulation varies the severity of these policy elements in several simulation jobs. 60 simulation jobs are conducted for 'Base', 'Replacement' and 'Regulation', respectively, and 12 for 'Investment' (Table 6.4 and Table 6.5). Within the variation, CO_2-prices assume values between 50 €/$t_{CO2\text{-}eq.}$ and 300 €/$t_{CO2\text{-}eq.}$ in 2030, the respective price-path is created by assuming a linear progression towards this value, starting with 8 €/$t_{CO2\text{-}eq.}$ in 2015. Operational subsidies are varied from 5 €ct/kWh to 20 €ct/kWh[79] (constant over time). These are capped when total process heat generation costs reach zero. This may already be the case for some consumer groups in the second or third subsidy level. In the final subsidy level, this is the case for the big majority of consumers.

[79] The difference between the highest and lowest industrial electricity price (Band IF: 70-150 GWh/a) is about 11 EUR/ct/kWh (2018) [45].

Table 6.4: Job index of parameter variation (CO_2-price and subsidies) for 'Base', 'Replacement' and 'Regulation'-scenario

Job number		CO_2-price in EUR/$t_{CO2\text{-eq.}}$											
		25	50	75	100	125	150	175	200	225	250	275	300
Subsidies in EURct/kWh	0	1	6	11	16	21	26	31	36	41	46	51	56
	5	2	7	12	17	22	27	32	37	42	47	52	57
	10	3	8	13	18	23	28	33	38	43	48	53	58
	15	4	9	14	19	24	29	34	39	44	49	54	59
	20	5	10	15	20	25	30	35	40	45	50	55	60

The parameter variation is performed with the open source tool Treez [47]. Treez remotely controls external executables as part of parameter studies. For each simulation job, an input file is generated and passed to the FORECAST executable. After the executable has been finished, specific results are collected by Treez in a global result database.

Table 6.5: Job index of parameter variation (CO_2-price and support) for 'Investment'-scenario

Job number		CO_2-price in EUR/$t_{CO2\text{-eq.}}$											
		25	50	75	100	125	150	175	200	225	250	275	300
Investment support	100%	1	6	11	16	21	26	31	36	41	46	51	56

6.3 Results

We first present the full range of range of all four scenario-variations with a focus on energy carrier use and emission reduction. Then, we investigate two result dimensions to eliminate parameter variations from the parameter-combinations available. First, the level of emission reduction, in which we eliminate all combinations that do not achieve the national sectoral target of between 140 $Mt_{CO2\text{-}eq.}$ and 143 $Mt_{CO2\text{-}eq.}$ in 2030, or overachieve it by more than 2 $Mt_{CO2\text{-}eq.}$. Second, we eliminate solutions that exceed the domestic sustainable biomass potential available to industry (assumed 75 TWh). The sustainability of current biomass production is, however, questionable and high standards on sustainability lower the yield per hectare considerably [48]. The given value is thus merely a rough estimate. We then pick a specific solution of the 'Regulation' scenario and present details of steam generation costs and cost components to explain the most influential effects of the investigated policies. Finally, we show emission reductions by technology field and identify sources that are not addressable with the presented approach.

6.3.1 Result range

The designed parameter variations (jobs) create solution spaces of energy carrier use[80] and energy- and process related emissions. In the following sections, a specific job will be picked for further analysis. The entire range for the respective jobs is shown in Figure 6.2. It shows the final energy demand for the energy carriers biomass, electricity, hard coal and natural gas as range within the parameter variation and by scenario. All scenarios and variations result in increased biomass and decreased coal use, but especially the 'Regulation' scenario opens a wide range. Increased Electricity use is an option in all scenarios but 'Investment'. Finally, natural gas use also remains on a high level in all scenarios. A substantial reduction of natural gas use is possible in the 'Replacement' scenario (with high subsidies for electricity) and the 'Regulation' scenario, where the fossil ban in 2025 has a high impact on gas use. This shows that in all parameter variations of the 'Regulation' scenario, natural gas is still an attractive option.

[80] We present data for the energy carrier natural gas, electricity, biomass and coal, which together, account for about 80% of final energy demand in all scenarios and variations. Other energy carrier included in the model but not shown here are ambient heat, coke, fuel oil, derived gases and waste.

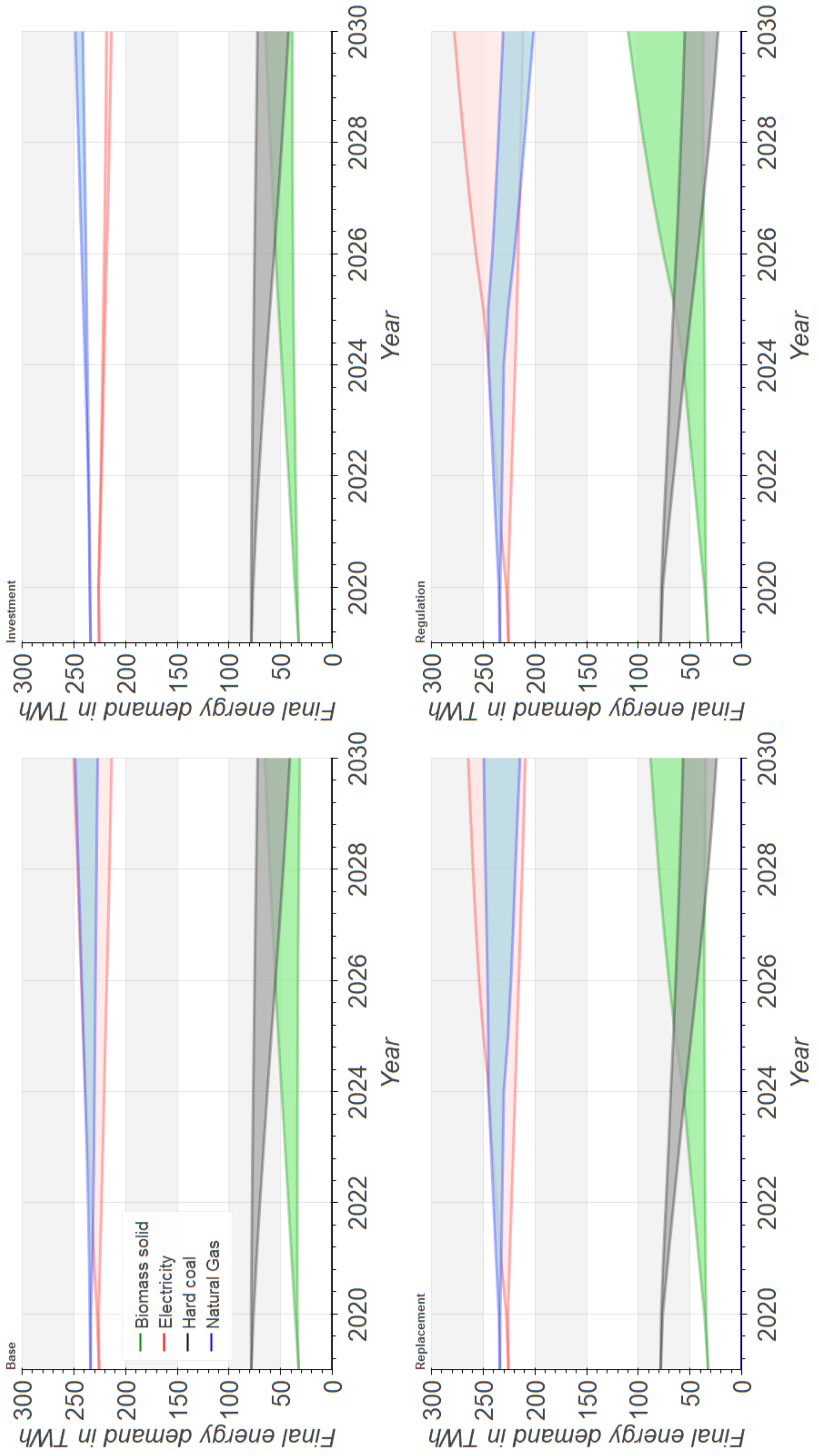

Figure 6.2: Range of final energy demand of selected energy carriers by scenario

6.3.2 Emission reduction

The combinations applied to the scenarios in this study (Table 6.6, Figure 6.3) generate a range of emissions in 2030 between 166 $Mt_{CO2\text{-}eq.}$ (job 1 in 'Base' scenario) and 128 $Mt_{CO2\text{-}eq.}$ (job 60 in 'Regulation' scenario). Of the 192 jobs, 99 do not achieve the national German policy target of at most 143 $Mt_{CO2\text{-}eq.}$ and none is on a 1.5°C-compatible pathway (102 $Mt_{CO2\text{-}eq.}$ in 2030). In the 'Base' and 'Investment' cases, no job achieves the sectoral target. In the 'Replacement' scenario, CO_2-prices between 75 and 175 €/$t_{CO2\text{-}eq.}$ are required to lower emissions below 143 $Mt_{CO2\text{-}eq.}$ in 2030. In this scenario, jobs achieving the target with CO_2-prices below 100 €/t_{CO2} require strong subsidies for electricity prices. All but the seven least ambitious 'Regulation' jobs achieve the sectoral German target, even at CO_2-prices as low as 25 €/$t_{CO2\text{-}eq.}$ (and strong electricity subsidies) or 75 €/$t_{CO2\text{-}eq.}$ (and weak subsidies). Within the same variation, the 'Regulation' scenario shows between 4 $Mt_{CO2\text{-}eq.}$ and 7 $Mt_{CO2\text{-}eq.}$ lower emissions than 'Replacement'. This can be interpreted as the effect of the ban for new fossil generation capacity. Comparing the 'Replacement' with the 'Base' scenario, the same parameter variations show a difference between 10 $Mt_{CO2\text{-}eq.}$ and 15 $Mt_{CO2\text{-}eq.}$. This can be interpreted as the effect of increased stock turnover.

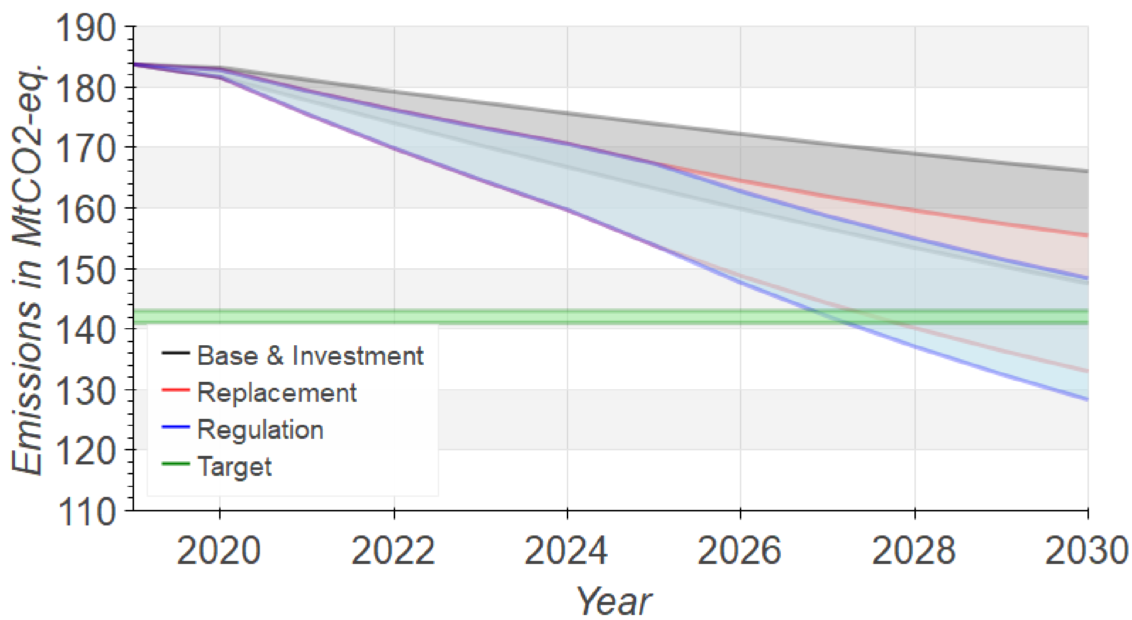

Figure 6.3: Emission ranges by scenario

Table 6.6: GHG-emissions (2030) in investigated parameter combinations of the base, incentive and regulatory scenario; grey background: emissions above or strongly below sectoral German policy target)

Base scenario													
Emissions in $Mt_{CO2-eq.}$		CO_2-price in EUR/$t_{CO2-eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	166	163	161	159	158	156	155	154	153	153	152	151
	5	163	160	159	157	156	155	154	153	152	152	151	150
	10	161	159	157	156	154	153	153	152	151	150	150	149
	15	159	157	156	154	153	152	152	151	150	149	149	148
	20	157	155	154	153	152	151	150	150	149	148	148	148
Investment scenario													
Emissions in $Mt_{CO2-eq.}$		CO_2-price in EUR/$t_{CO2-eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Investment support	**100%**	166	163	161	159	158	156	155	154	153	153	152	151
Replacement scenario													
Emissions in $Mt_{CO2-eq.}$		CO_2-price in EUR/$t_{CO2-eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	155	152	150	148	146	144	143	142	141	140	139	138
	5	153	150	148	146	144	143	142	141	140	139	138	137
	10	151	148	146	144	142	141	140	139	138	137	136	136
	15	149	146	144	142	141	139	138	137	137	136	135	134
	20	146	143	142	140	139	138	137	136	135	134	134	133
Regulation scenario													
Emissions in $Mt_{CO2-eq.}$		CO_2-price in EUR/$t_{CO2-eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	148	145	143	141	139	138	137	136	135	134	133	132
	5	148	145	143	141	139	138	137	136	135	134	133	132
	10	146	143	141	139	138	136	135	134	133	133	132	131
	15	144	141	139	137	136	135	134	133	132	131	130	130
	20	141	139	137	135	134	133	132	131	130	130	129	128

6.3.3 Biomass use

In all jobs, the use of biomass and biomass-derived fuels, especially in high-temperature applications, is a major option for emission reduction. Deemed CO_2-neutral in terms of direct emissions, its relative attractivity is strongly increased by high CO_2-prices (Table 6.7). Its use rises by approximately 2-5 TWh per 50 €/$t_{CO2-eq.}$ price increase, while it decreases by up to 13 TWh (33 TWh in 'Regulation') per level of electricity subsidies (5 €ct/kWh per level)[81]. Compared to 2015's industrial use of close to 30 TWh [29], most scenarios and jobs see a strong increase, up to 111 TWh in the high CO_2-price variations of the 'Regulation' scenario. Some jobs thus exceed the assumed sustainable domestic potential of 75 TWh. Those are excluded from the potential solutions. In the 'Replacement' and 'Regulation' scenario, 11 and 5 jobs remain, respectively. For further analysis, we pick jobs 1 (0 €/$t_{CO2-eq.}$, 0 €ct/kWh) and 60 (300 €/$t_{CO2-eq.}$, 20 €ct/kWh) in the 'Base' scenario, job 15 (75 €/$t_{CO2-eq.}$, 20 €ct/kWh) in the 'Replacement' scenario and job 12 (75 €/$t_{CO2-eq.}$, 5 €ct/kWh) in the 'Regulation' scenario. The latter two achieve similar emission reduction.

81 Higher level of electricity subsidies show diminishing returns, as the subsidy is capped at zero heat generation costs. Applications that reach those at a given subsidy level, are not influenced by the next one.

Table 6.7: Biomass use by job (2030), grey font: jobs previously excluded, grey background: jobs exceeding assumed sustainable biomass potential (75 TWh), bold: picked for further analysis

Base													
Biomass use in TWh		CO₂-price in EUR/$t_{CO2\text{-}eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	**39**	43	46	49	51	54	56	58	61	63	64	66
	5	35	37	39	40	42	44	45	47	49	51	52	54
	10	33	35	36	37	39	41	42	43	45	47	48	50
	15	33	34	36	37	38	40	41	42	44	46	47	48
	20	32	33	34	36	37	38	40	41	43	44	45	**47**
Investment													
Biomass use in TWh		CO₂-price in EUR/$t_{CO2\text{-}eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Investment support	**100%**	39	43	45	48	51	54	56	58	60	62	63	65
Replacement													
Biomass use in TWh		CO₂-price in EUR/$t_{CO2\text{-}eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	55	60	63	67	71	74	77	79	82	83	87	89
	5	44	47	49	52	55	58	61	64	66	68	72	74
	10	39	42	44	46	49	51	54	56	59	61	64	66
	15	38	40	42	44	47	49	51	53	56	58	61	63
	20	35	37	**39**	41	43	45	48	50	52	54	56	58
Regulation													
Biomass use in TWh		CO₂-price in EUR/$t_{CO2\text{-}eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	84	87	90	92	95	98	100	103	105	106	109	111
	5	53	56	**59**	61	64	67	69	72	74	76	79	81
	10	45	48	50	52	55	57	59	62	64	66	69	71
	15	42	44	46	49	51	53	55	58	60	62	64	66
	20	37	39	41	43	45	47	50	52	54	56	58	60

6.3.4 Electricity use

The increased use of electricity for process heat is in general not attractive (Table 6.8). Without the additional subsidies considered in the respective jobs in 'Base', 'Replacement' and 'Regulation' scenario, even high CO_2-prices increase electricity use by just 5-8 TWh. Subsidies for investments in electricity-based heating systems ('Investment' scenario) of 100% have a negligible effect (below 0.5 TWh). Electricity use strongly increases in jobs with subsidies on operational expenses. In the 'Base' scenario, each step of 5 €ct/kWh subsidy increases electricity use by 6 to 10 TWh, depending on CO_2-price and previous subsidy level. This effect is increased in the 'Replacement' scenario (9-11 TWh) and the 'Regulation' scenario (11-13 TWh). The final modelled step to 20 €ct/kWh, essentially providing free electricity for all consumer groups, is especially effective (up to 18 TWh increased electricity use in 'Regulation').

The different use patterns of electricity and biomass in the presented jobs show that an increase of the CO2-price is of little relevance for the attractivity of electricity for process heating, but substantially increases biomass attractivity. We consider this to be the effect of the strong difference of heat generation costs between natural gas and biomass on the on hand and electricity-based systems on the other hand. This is further explained in section 6.3.6.

Table 6.8: Electricity use by job (2030)

Base													
Electricity use in TWh		CO_2-price in EUR/$t_{CO2\text{-}eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	213	214	214	215	215	216	216	217	217	218	218	218
	5	221	222	222	223	223	224	224	225	225	225	226	226
	10	228	229	229	230	231	231	232	232	233	233	233	233
	15	234	235	236	237	238	238	239	239	240	240	240	240
	20	245	247	247	248	248	249	249	249	250	250	250	250
Investment													
Electricity use in TWh		CO_2-price in EUR/$t_{CO2\text{-}eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Investment support	**100%**	214	214	215	215	216	216	217	217	217	218	218	219
Replacement													
Electricity use in TWh		CO_2-price in EUR/$t_{CO2\text{-}eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	209	210	211	212	213	213	214	215	215	216	217	217
	5	219	221	221	222	223	224	224	225	225	226	226	226
	10	230	232	233	234	235	235	236	237	237	237	238	238
	15	241	243	244	245	246	247	247	248	248	248	249	249
	20	259	261	261	263	263	263	264	264	264	264	264	264
Regulation													
Electricity use in TWh		CO_2-price in EUR/$t_{CO2\text{-}eq.}$											
		25	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Subsidies in EURct/kWh	**0**	212	212	213	214	215	215	216	217	217	218	218	219
	5	225	226	227	227	228	229	229	230	230	231	231	232
	10	236	238	239	240	241	241	242	243	243	244	244	244
	15	249	251	252	253	255	255	256	257	257	257	258	258
	20	272	273	275	275	276	277	277	278	278	278	278	278

6.3.5 Emissions by technology field

The FORECAST model considers several areas of energy use, named technology fields. These contain grouped applications and emissions sources, which tend to use similar technologies and show common use patters. The technology fields are industrial furnaces, steam demand, process related emissions and space heating. Summed with a calibration difference, they form the emission balance (Figure 6.4). In all scenarios, the process related emissions decrease from 43 to 35 $Mt_{CO2\text{-}eq.}$ until 2030, which is caused by the exogenous assumption of a reduction of HFC by 70%. This reduction is thus not price-sensitive. Emissions caused by high-temperature energy use in industrial furnaces reach, with high CO_2-prices and/or electricity subsidies, values between 74 $Mt_{CO2\text{-}eq.}$and 79 $Mt_{CO2\text{-}eq}$. This reflects a moderate reduction given the high incentives. Reasons for the low price sensitivity are among others technical fuel-switch limitations like for example the minimum need for coal in the blast furnace. High price-sensitivity and immediate short-term emission reduction potential can be observed in steam generation. Especially a higher stock exchange rate in the 'Replacement' scenario and a fossil ban on new installations in the 'Regulation' scenario increase the achievable emission reduction. Comparing the technology-field specific emission reduction of all jobs in all scenarios shows that the introduction of faster stock exchange ('Replacement' scenario) and the ban on new fossil-based steam generation ('Regulation' scenario) relieves pressure from industrial furnaces, as the necessary price signals are reduced (Figure 6.5).

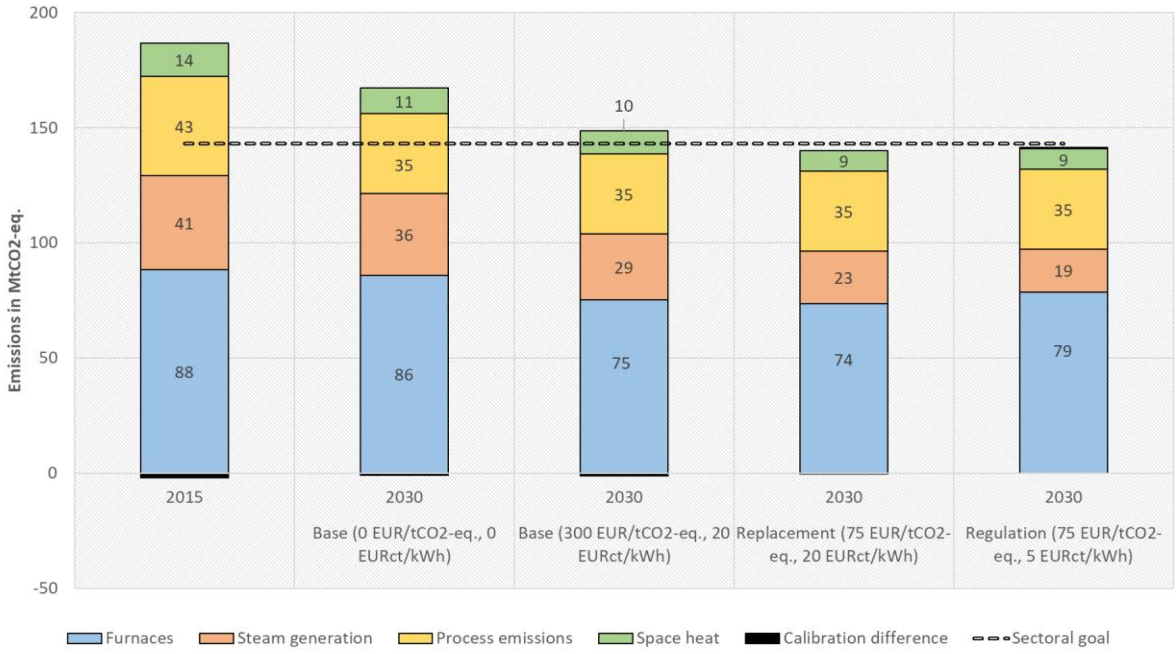

Figure 6.4: GHG-emissions by technology field for selected jobs in 2015 and 2030

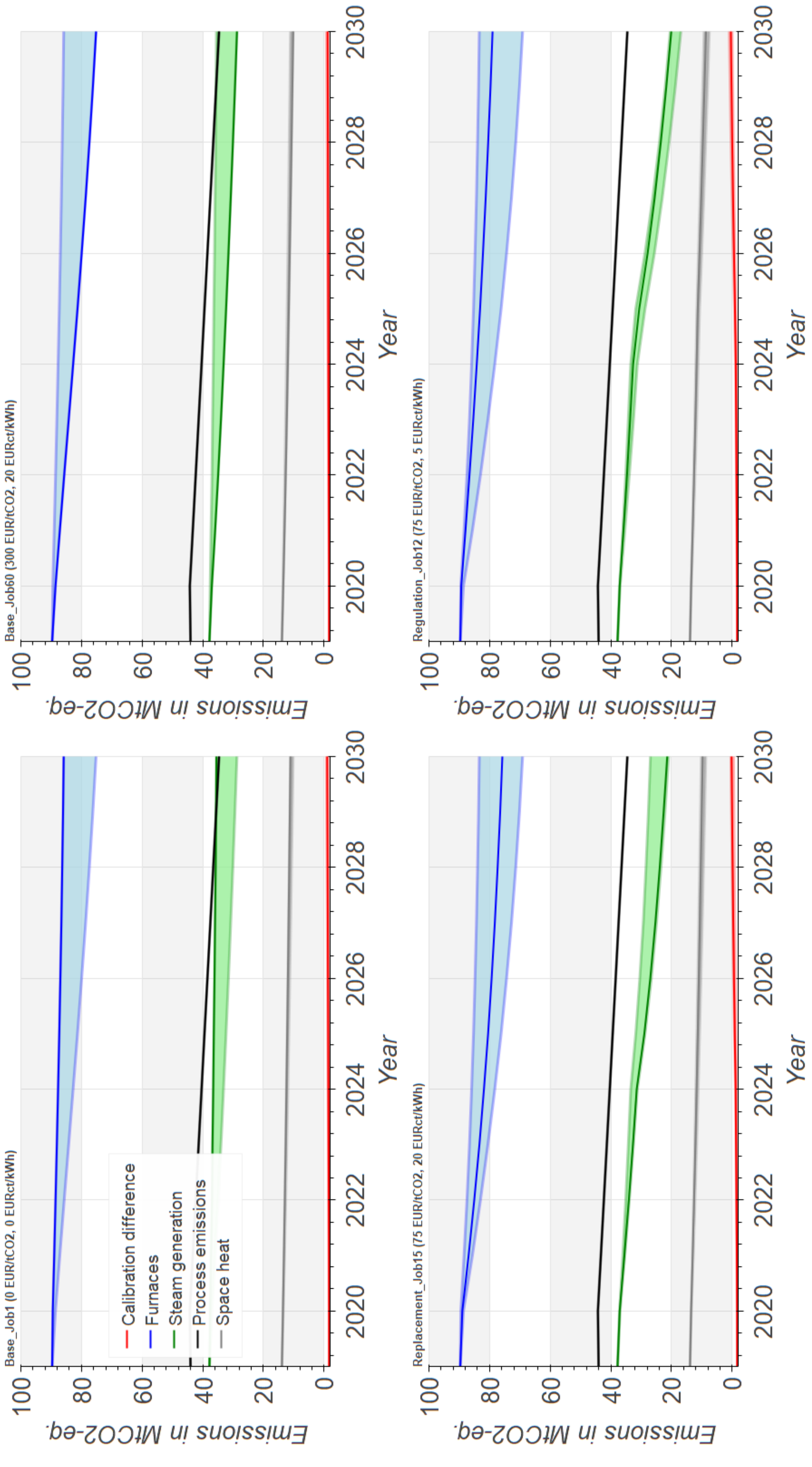

Figure 6.5: GHG-emissions by scenario, range of all jobs (area) and selected jobs (line)

6.3.6 Heat generation costs of steam systems

In the technology field steam generation, heat generation costs are the main criterion for system attractiveness. They are affected by the investigated parameter variation of CO_2-price and electricity subsidy. Figure 6.6 presents the heat generation costs for the main competing technologies natural gas boiler, heat pump (electric), biomass boiler and electric boiler[82].

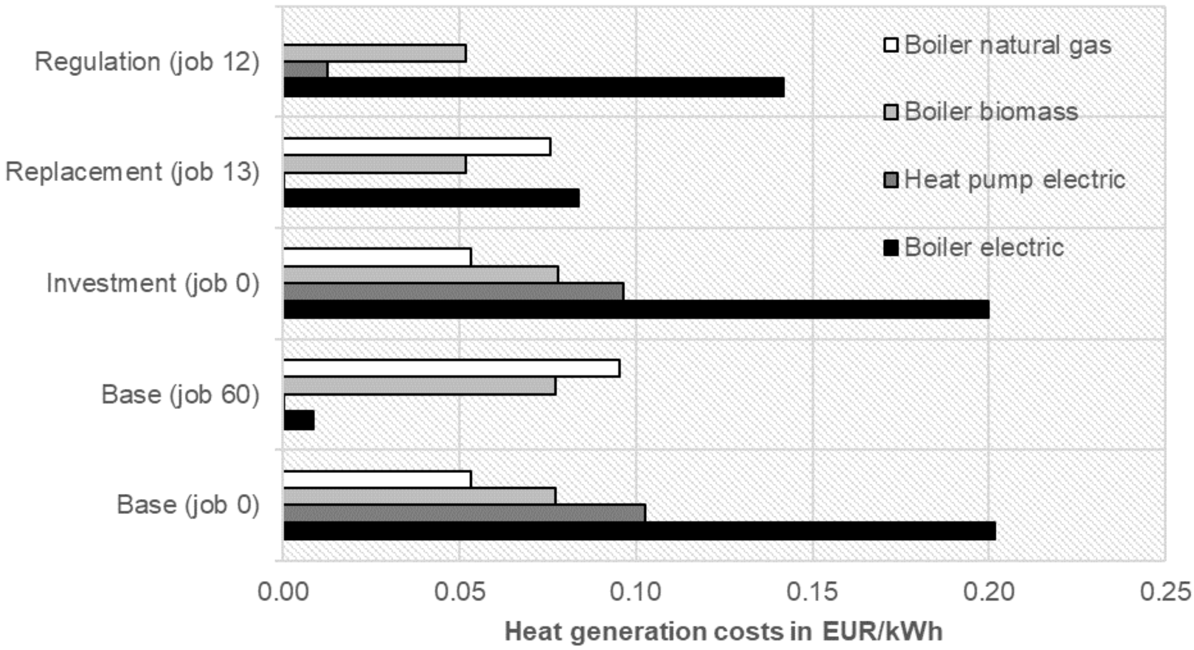

Figure 6.6: Heat generation costs of selected systems in different scenario variations, 2030 (job 0: 0 €/$t_{CO2\text{-}eq.}$, 0 €ct/kWh, job 60: 300 €/$t_{CO2\text{-}eq.}$, 20 €ct/kWh, job 12: 75 €/$t_{CO2\text{-}eq.}$, 5 €ct/kWh, job 13: 75 €/$t_{CO2\text{-}eq.}$, 10 €ct/kWh)

In the 'Base' scenario without CO_2 price or support for electric heat generation (job 1), natural-gas fired boilers are the most economic solution (5 €ct/kWh). Biomass boilers are close to being competitive (8 €ct/kWh), but both electric heat pumps (10 €ct/kWh) and electric boilers (20 €ct/kWh) are not. The investment scenario includes a grant of 100% on the investment for heat pumps and electric boilers. The results show that even investment support of 100% for electric boilers do not substantially improve the competitieveness ('Investment' scenario), reducing the heat generation costs of electric boilers by less than 1 €ct/kWh. This reflects the high importance of operational costs as compared to the investment for electric boilers (driven by high annual fullload hours combined with large units). More specifically, the investment only makes about 5% of the total costs of ownership

82 Systems with combined heat and power generation are also modeled. They behave similar to the technologies presented here. Although they are more capital intensive in general, their operational expenses also dominate the heat generation costs.

for an electric boiler (that is running in base load). A similar grant for heat pumps shows higher effect, but also no fundamental improvement to their competitiveness.

In high-price jobs of the 'Base' scenario, the CO_2-price almost doubles the heat generation costs of natural gas-fired boilers to 9.5 €ct/kWh, which is higher than for biomass boilers. Further, subsidies on the electricity use create heat generation costs of electricity-based systems between 0 €ct/kWh (electric heat pump) and 1 €ct/kWh (electric boiler). The resulting emission reduction is (Figure 6.4) still short of the set targets for 2030: Although virtually all new installations are either biomass or electricity-based systems, the existing stock is not exchanged fast enough. With the increased stock exchange in the 'Replacement' scenario, the targets are met even on substantially lower CO_2-prices, while the overall picture of heat generation costs does not change. Finally, in the 'Regulation' scenario, natural gas-fired boilers are banned[83] and thus biomass boilers are the most cost-effective solution even on comparably low CO_2-price levels. The potential of electric heat pumps to supply low-temperature heat suffices to keep the biomass use below the assumed sustainable potential. Electric boilers are not used in this job due to higher heat supply costs. For the 'Replacement' and 'Regulation' scenario, both policy combinations (high CO_2-price and low subsidy or vice-versa) are possible (cf. Table 6.6).

6.3.7 Cost components

We distinguish five cost components that determine the total costs of a steam generation system: CO_2-related costs, fuel costs, CAPEX, OPEX (excluding fuel) and subsidies/income[84] (Figure 6.7). However, for separated heat producers (SHP, as opposed to combined heat and power generation, CHP), both CAPEX and non-fuel related OPEX are negligible. The fuel costs often make up for about 95% of the entire costs, only rivalled by CO_2-costs in high CO_2-price variations. Especially electric boiler show a low share of CAPEX on total costs, as the energy carrier price is very high. It is therefore not surprising that even high investment support (100% in scenario 'Investment') does not increase the attractivity of electric boilers considerably, while subsidies on fuel costs do (cf. Table 6.6). Main reasons explaining the high importance of energy costs are the high annual running hours combined with the use of large units allowing low specific investment costs (especially compared to residential sector heating applications).

In Figure 6.7, the relative cost component shares for selected technologies are presented for two jobs in the 'Base' scenario. The first job with a target CO2-price of 0 €/$t_{CO2\text{-}eq.}$ in 2030 shows that fuel costs are the single most relevant cost component. The second job a target CO2-price of 300 €/$t_{CO2\text{-}eq.}$ in 2030 shifts the cost structure of natural gas boilers considerably, almost doubling the system costs.

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83 Thus not displayed in Figure 6.6.

84 E.g. from avoided electricity purchase or sold electricity in the case of CHP.

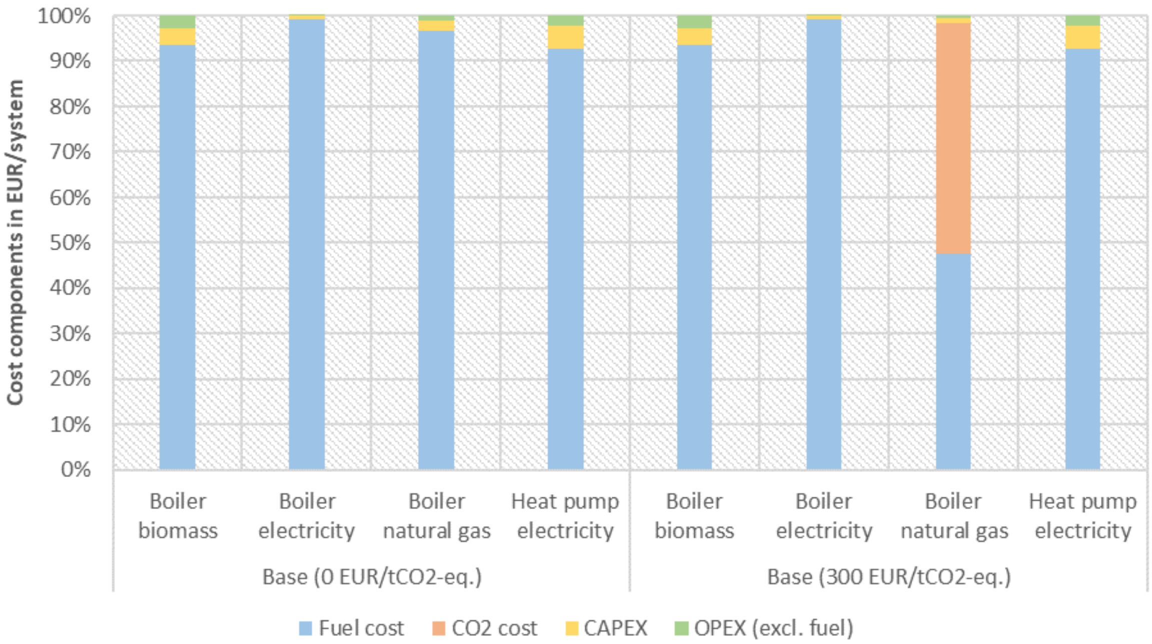

Figure 6.7: Cost components of a representative system (selected technologies) with low and high CO2-prices in the 'Base' scenario and system costs

6.3.8 System costs

The heat generation costs and cost components are relevant for investment decisions and influence the attractivity of technologies. From a societal point of view, the costs of the investigated energy system are more important. In this section, we therefore analyse which solution, with the goal to supply the same service (here: generation of process heat), has low costs and offers GHG-emissions reduction. To this end, we present the three most relevant cost components: First, energy related costs, which are caused by the purchase of fuel or electricity. Second, the annuity of investment, caused by deprecation of investments over the lifetime of the installations[85]. Third, the direct costs of the investigated policy measures CO_2-price and subsidies for electricity-based process heat. The resulting system costs, the sum of these components, are presented over the GHG-emissions (Figure 6.8). The jobs previously presented create a range of 85 to 145 billion € system costs (70% increase) and additional emissions reductions of up to 38 Mt. In this representation, increasing CO_2-prices create a skewed line of GHG-emission reduction, while electricity subsidies create upwards and left shifted steps. This effect is more pronounced in scenarios with high exchange rates, as the ability to react to price signals is higher.

[85] Note that this assumes a societal perspective rather than n individual or company-based perspective. In the latter, the deprecation period is shorter and thus the annuity higher.

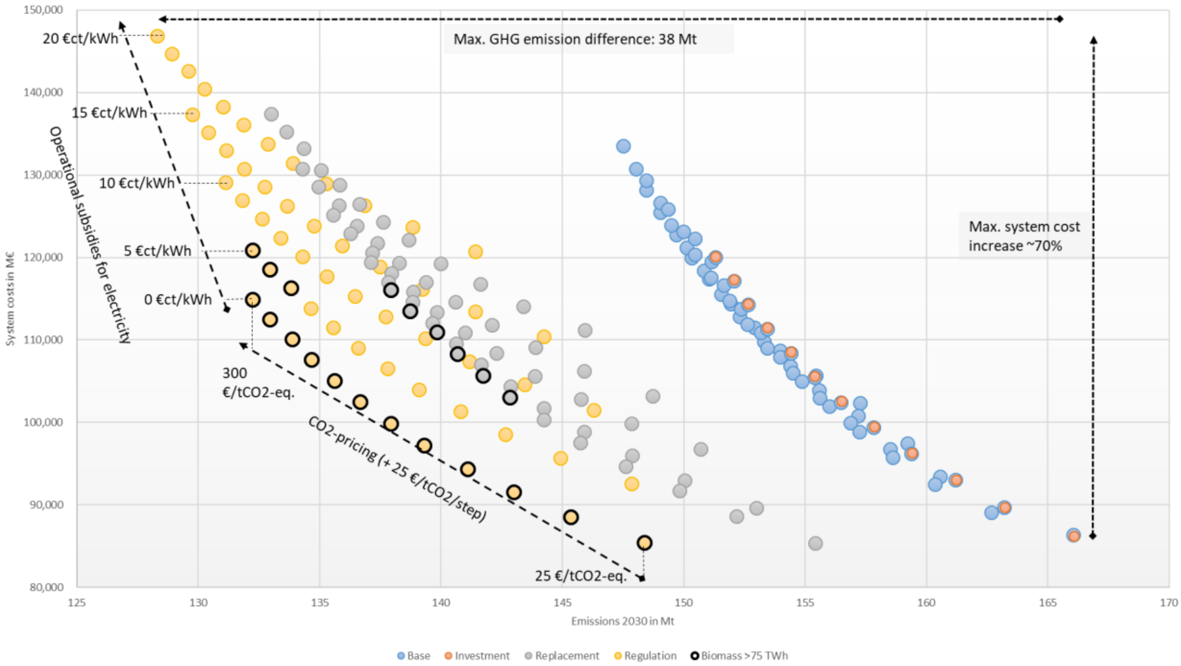

Figure 6.8: System cost over GHG emissions for variations of electricity subsidies and CO_2-price (explanation)

Figure 6.9 adds interpretation to the results, highlighting observations of interest:

- The introduction of regulatory measures may yield similar system costs as the 'Replacement' scenario, while increasing emission savings (1)
- A faster replacement of existing installations has a high effect on emission reduction but only a limited effect on system costs (shift almost parallel to x-axis from 'Base' to 'Replacement', 2)
- Under certain conditions, an increase of subsidies on electricity-based process heating does not yield any emission savings but only increases system costs (3). This is caused by the high difference is heat generation costs and the consequently low attractivity of electricity-based systems. It might also hint at windfall profits.
- While the 'Base' scenario does not reach the emission reduction target range, 'Regulation' may reach it with a system cost increase of about 15% (without exceeding the assumed biomass limit, 4).
- The 'Replacement' scenario reaches the target range with a system cost increase of about 20% (5).
- Higher levels of CO2-pricing show diminishing returns in terms of emission reduction (purple).
- Subsidies on investments in process heat generation do not yield substantial effects on emission reduction (red). This observation can be explained with the low share of capital expenditures on the total heat generation costs (Figure 6.7).

- The results in the 'Base' scenario are in a tight group, indicating a lack of flexibility to react to price signals. This highlights that a faster replacement of installations is required.

The policy measures investigated here influence the competition between biomass- and electricity-based heating. The direct comparison of their use (Figure 6.10), highlights the policy effect. The CO_2-price mainly supports biomass use and has little effect on the attractivity of electricity. The direct support of heat generation costs from electricity is needed to increase electricity use substantially. The system costs increase with both policy measures, but jobs within the target range of 141 - 143 $Mt_{CO2\text{-}eq.}$ show lower system costs (92 $*10^9$ €) with higher shares of biomass. However, these solutions exceed the set biomass limit of 75 TWh. Jobs with high electricity use within the target range have system costs of up to $124*10^9$ €. Jobs within the target range show a minimum demand of biomass and electricity (for process heating) combined of 135 TWh and a maximum of 161 TWh. However, in the 'Base' scenario, some jobs reach the same values but are still short of the emission target.

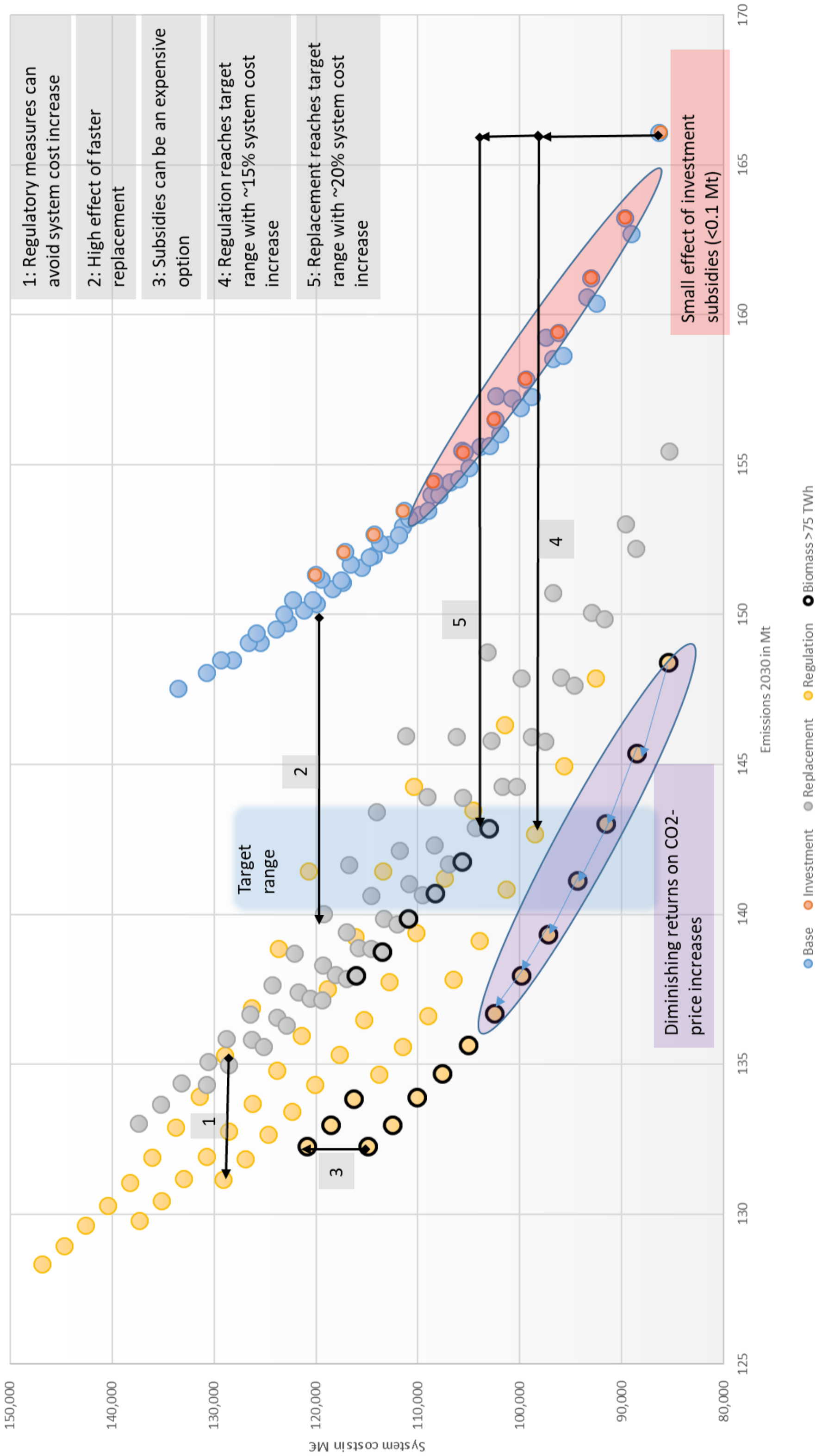

Figure 6.9: System cost over GHG emissions for variations of electricity subsidies and CO2-price (interpretation)

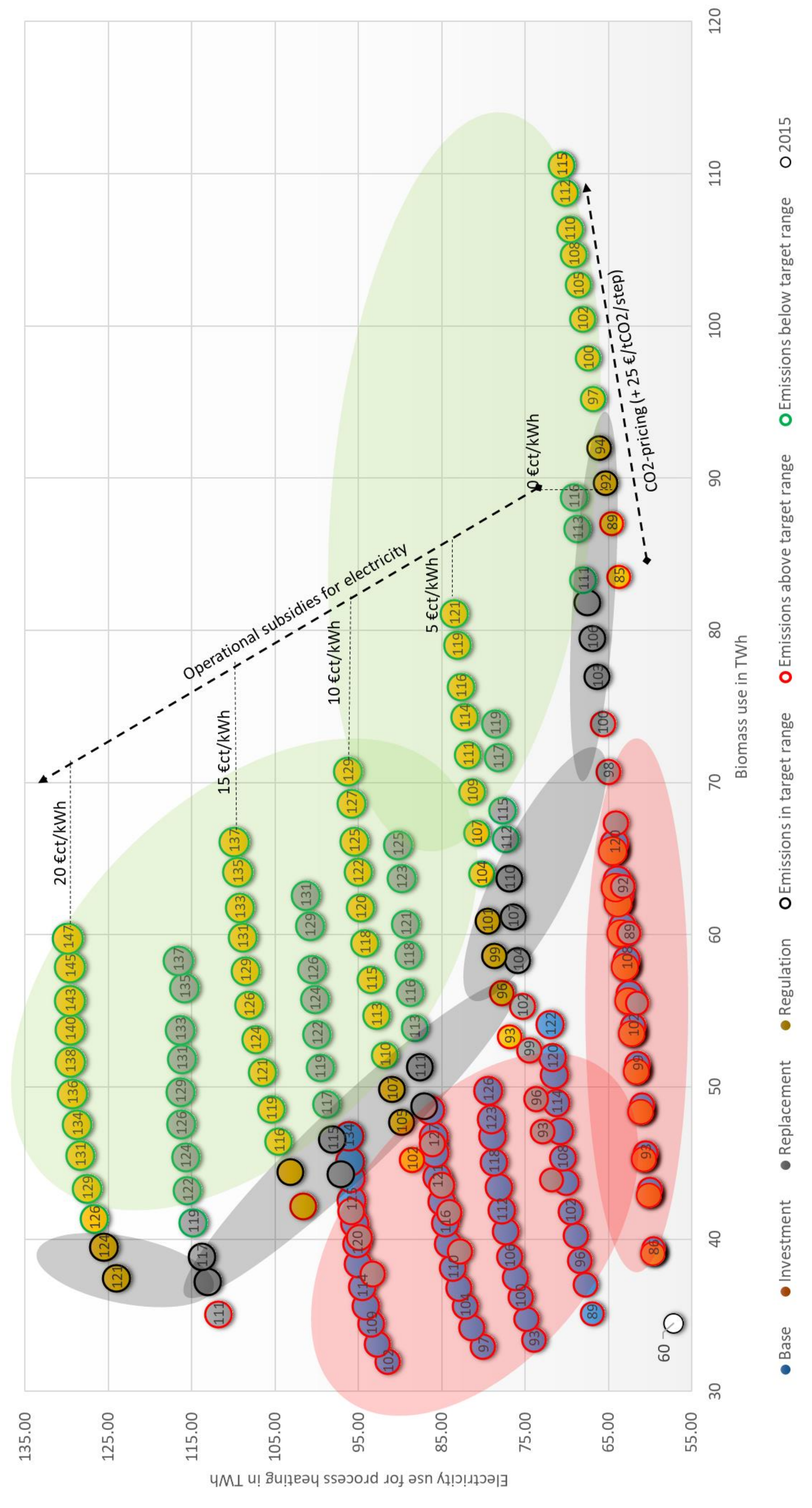

Figure 6.10: Biomass and electricity use by scenario (2030); bubble size and labels show system costs in 10^9 €

6.3.9 Remaining emissions

Although the currently included economic incentives can achieve pathways compatible with the national German 2030 target, considerable emission sources are not addressed (Table 6.9). In the jobs reaching the target, the use of coal in the iron and steel industry is already reduced by 29 % compared to 2015. Still, almost 22 $Mt_{CO2\text{-}eq.}$ remain in 2030, mostly because coke use in blast furnaces is less price sensitive. Process-related emissions are not addressed in this study[86] as they are not affected by fuel choice, but they account for almost 30 $Mt_{CO2\text{-}eq.}$ in 2015 and 2030.

Table 6.9: Sources of large remaining emission groups

Source	*Emissions 2015 [Mt]*	*Emissions 2030 [Mt]*
NM-minerals: process emissions	18.43	20.19
Chemical industry: process emissions	6.77	6.65
Iron and steel: process emissions	2.31	2.25
Non-ferrous metals: process emissions	1.35	1.28
Sum process-related	**28.86**	**30.37**
Iron and steel: coal and coke use	30.42	21.67
Sum	**59.28**	**52.04**

With the goal to reach net-neutrality in 2050 however, these emissions must be avoided. To this end, innovative processes [49] are being discussed that can reduce the dependence on specific energy carriers, materials and process conditions (Table 6.10). Important examples are hydrogen-based ironmaking and chemistry or new cement types. In addition, carbon capture and storage may be applied, especially to address large process-related emission sources where other technical options are less obvious.

[86] Excluding HFC and other product-use emissions.

Table 6.10: Process-related emissions[1] and options to address them until 2050

Emissions 2030 [Mt]	*Process*	*Subsector*	*Address with*
12.01	Clinker calcination	NM-minerals	New cement types, CCS
5.23	Lime burning	NM-minerals	CCS
3.89	Ammonia	Chemical industry	H2-feedstock
1.69	Sinter	Iron and steel	Replacing BF
1.67	Carbon black	Chemical industry	-
1.01	Aluminium, primary	NF-metals	Inert anode
0.86	Tiles, plates, refractories	NM-minerals	-
0.85	Other ceramics	NM-minerals	-
0.49	Poly ethylene	Chemical industry	H2-feedstock
0.46	BF	Iron and steel	Replacing BF
0.42	Soda ash	Chemical industry	-
0.38	Flat glass	NM-minerals	Cold top-furnace
0.35	Bricks	NM-minerals	-
0.27	Zinc, primary	NF-metals	-
0.25	Container glass	NM-minerals	Cold top-furnace
0.17	Nitric acid	Chemical industry	-
0.11	EAF	Iron and steel	-
0.1	Fibre glass	NM-minerals	-
0.1	Sanitary ware	NM-minerals	-
0.05	Other glass	NM-minerals	-
0.01	Calcium carbide	Chemical industry	-
30.37	**Sum**		**25.4**

1: Emissions are scaled to match CRF-system. Bottom-up calculations show higher emissions, e.g. 5.6 Mt_{CO2-eq}. in lime production. In total, bottom-up calculations of process-related emissions are about 10% higher.

6.4 Discussion

One of the most influential factors determining the achievable emission reduction is the rate of stock exchange of process heat generation capacities. In the 'Base' scenario, only economic incentives are applied. Increasing prices do not affect the rate of stock exchange, which is merely determined by the age distribution of the technology stock. The price sensitivity is mainly determined by the behavioural parameters used in the model, which do not change during the modelled period. One may argue that strong economic pressure, e.g. caused by high CO_2-prices, changes behavioural patterns, supporting faster adaption and stock exchange before the equipment's' end-of-life. The results presented in the 'Base' scenario may thus underestimate the dynamics strong price signals can trigger.

The switch to electricity for process heating relies on the transformation sector's fast decarbonisation. In the current energy system, direct electricity use has a higher emission factor than natural gas. Given the path-dependency of the technological stock in the industry sector, it is necessary to incentivize fuel switch to electricity. For individual investment decisions, the entire lifetime of an installation must be considered to determine the ecologic benefit. This would justify replacing installations even if they may increase emissions in the short-term. Not building new fossil-based installations is just as important as replacing old ones.

The presented investigation is limited to a narrow band of policy measures and GHG reduction actions. In particular, material efficiency, circular economy, production shifts and interaction with other sector (e.g. hydrogen-based economy) are not considered here but are important fields of action. While our intention was to assess the contribution of fuel switch to meeting 2030 GHG targets, designing the full policy mix certainly requires to also draw a policy elements from these other fields. While we have aimed to investigate uncertainties and worked with ranges for key assumptions, there is still high uncertainty in many parameters. Different assumptions on the underlying industrial production output or energy carrier prices can have a strong effect on the resulting GHG emissions in 2030 and the conclusions on target achievement. The steel industry, for example, is (with 63 $Mt_{CO2-eq.}$ in the base scenario 2030) a major contributor to GHG-emissions. A demand reduction by 20% in this sector alone may reduce emissions by approximately 12 $Mt_{CO2-eq.}$ This is similar to the emission reduction difference found between the 'Base' and 'Replacement' scenario. In addition, a faster switch to electric steel can have a potentially high impact. Thus, this work presents lessons learned on important mechanisms for fuel switch and the relation to economic incentives, but does not make predictions on the future industrial GHG emissions.

This research is based on the latest available confirmed emissions in the CRF-framework for 2015 to compare them with the climate targets. However, official data for 2017 reveals a relevant increase of GHG-emissions from 184.7 $Mt_{CO2-eq.}$ (2015) to 196.3 $Mt_{CO2-eq.}$ (2017), mainly caused by higher energy-related emissions. Achieving the climate targets in 2030 requires thus even more ambition. This highlights the need for immediate action to stop the current trend and return the sector on a reduction path.

6.5 Summary and Conclusion

In this article, we explore the impact of economic and regulatory policies in the industrial sector on the German sectoral GHG emission reduction target in 2030. The investigation focuses on technology-specific subsidies for electricity-based heat generation and CO_2-pricing. We apply a parameter variation to find combinations of these policy measures that achieve the national German GHG target for the industrial sector (between 140 $Mt_{CO2\text{-}eq.}$ and 143 $Mt_{CO2\text{-}eq.}$) in 2030. The analysis is carried out with the energy demand simulation model FORECAST. We analyse the results of four scenarios and additional parameter variation, resulting in 192 scenario combinations. Results show that 2030-targets cannot be achieved with economic incentives for fuel switching alone, under the assumptions taken for equipment stock turnover and industrial production output. A transformation fast enough to comply with the target requires high CO_2-prices to disincentivize fossil fuel use (between 75 €/$t_{CO2\text{-}eq.}$ and 175 €/$t_{CO2\text{-}eq.}$ in 2030), combined with high subsidies for electricity-based process heat generation (up to virtually free electricity for process heat purposes) and a high stock exchange rate until 2030. A ban on fossil-based low- to medium-temperature process heat generation, most importantly natural gas, lowers the required subsidies and CO_2-prices substantially.

Subsidies or grants to lower the CAPEX of renewable-based heat supply technologies like electric boilers has virtually no impact on the cost-effectiveness of the alternative supply options and consequently the market shares. They reduce the heat generation costs, which we use as major criterion for technology attractivity, by less than 1 €ct/kWh (5%) in the case of electric boilers. The reason behind this phenomenon is that over the lifetime of an installation, investment has a negligible share in the total costs of ownership, while they are dominated by energy expenditures. We conclude that an effective policy mix to incentivise fuel switching to electricity needs to address the operational expenditures rather than the capital expenditures.

All investigated parameter combinations of CO_2-price and electricity subsidies show a mixture of biomass and electricity use to replace coal and natural gas. Ambitious scenarios only including a CO_2 price show a very high importance of biomass until 2030 often exceeding the assumed sustainable potential of 75 TWh. Consequently, the CO_2 price does not automatically introduce electric boilers into the market, because biomass is always the cheaper option. A higher contribution of electric heating requires specific incentives targeting the energy expenditures of electric heating units separately. Subsidies on electricity-based heat generation in the order of magnitude of 5 €ct/kWh suffice to make heat pumps cost-competitive in most low-temperature applications. High electricity subsidies (10-15 €ct/kWh) are needed to enable electric steam boilers as competitor to biomass-based steam generation. To put this into perspective: the electricity price advantage of industrial consumers exempt from many price components in today's German legislative framework ranges between 8 and 12 €ct/kWh. Higher subsidies enable a faster transition and influence the required CO_2-price.

The measures considered in the 'Regulation' scenario do however not suffice, even in high price variations, to achieve emission reduction compatible with 1.5°C IPCC scenarios. The main reason is the inflexibility of process emissions and parts of high-temperature demand in several important industrial processes (e.g. iron making). Thus, to bring the industry on a path towards CO_2-neutrality, additional mitigation options including for example circular economy, material and energy efficiency, process switch to new CO_2-neutral technologies and secondary energy carriers like hydrogen are needed. While we have only looked at the potential of fuel switch, future work should close this gap and model fuel switch, material and energy efficiency, circular economy, sufficiency and process change in a combined approach.

The results show that fuel switch can contribute considerably to the national German targets for the industry sector in 2030. However, the price corridors proposed by the German Federal Government [36] are, on their own, not sufficient to incentivize fuel switch compatible with the sectoral targets for the German industry in 2030. The emission reduction effect of price paths similar to the proposed minimum (35 €/$t_{CO2\text{-}eq.}$) and maximum price (60 €/$t_{CO2\text{-}eq.}$) amounts to 3.5 $Mt_{CO2\text{-}eq.}$ compared to 25 €/$t_{CO2\text{-}eq.}$ (cf. Table 6.6), CO_2-price between 50 and 75 €/$t_{CO2\text{-}eq.}$). In particular, this price level is unable to support electricity use for process heating, instead at best supporting biomass. The results also show that market-based measures alone require strong and early price signals to be effective. Due to the mismatch of natural reinvestment cycles and remaining time to reach the targets, they are, on their own, also ineffective. A higher exchange rate of process heat installations is necessary to reach 2030 targets, increasing modelled system costs by about 20% compared to the 'Base' scenario (which does not reach the emission reduction target). The introduction of regulatory measures such as a fossil ban may reduce the system cost increase to 15%.

Table 6.11: Assumed activity by industrial process in all scenarios (in Mt)

Subsector	***Process***	***2015***	***2030***
Chemical industry	Adipic acid	0.51	0.51
	Ammonia	2.85	2.98
	Calcium carbide	0.19	0.19
	Carbon black	0.92	0.92
	Chlorine, diaphragm	1.14	1.13
	Chlorine, membrane	3.05	4.03
	Chlorine, mercury	0.60	0.00
	Ethylene	5.13	5.90
	Methanol	0.98	1.02
	Nitric acid	2.48	2.48
	Oxygen	8.69	8.69
	Poly carbonate	0.50	0.73
	Poly ethylene	1.62	1.80
	Poly propylene	1.71	1.90
	Poly sulfones	0.41	0.59
	Soda ash	2.63	2.63
	TDI	0.48	0.64
	Titanium dioxide	0.46	0.53
Food, drink and tobacco	Bread & bakery	5.77	5.69
	Brewing	8.54	8.43
	Dairy	17.82	17.59
	Meat processing	11.95	11.80
	Sugar	3.89	3.74
Iron and steel	Blast furnace and converter	30.05	31.42
	Coke oven	8.82	8.51
	Direct reduction	0.56	0.56
	Electric arc furnace	12.62	14.80
	Rolled steel	36.55	39.58
	Sinter	26.30	25.65
Non-ferrous metals	Aluminium rolling	2.24	2.23
	Aluminium extruding	0.68	0.68
	Aluminium foundries	0.96	0.96
	Aluminium, primary	0.53	0.50
	Aluminium, secondary	0.64	0.67
	Copper further treatment	1.81	1.81
	Copper, primary	0.36	0.36
	Copper, secondary	0.30	0.30
	Zinc, primary	0.17	0.17
	Zinc, secondary	0.09	0.09
Non-metallic mineral products	Bricks	13.35	13.18
	Cement grinding	31.16	35.28
	Clinker calcination-dry	22.31	24.39
	Container glass	5.01	4.43
	Fibre glass	0.89	0.95
	Flat glass	2.41	2.17
	Gypsum	17.18	17.18
	Houseware, sanitary ware	0.05	0.05
	Lime burning	6.66	7.55
	Lime milling	5.00	5.66
	Other glass	0.41	0.38
	Preparation of limestone	23.80	25.38
	Technical, other ceramics	0.24	0.24
	Tiles, plates, refractories	2.25	2.38
Other non-classified	Blow moulding	1.00	1.11
	Extrusion	4.54	5.04
	Injection moulding	2.29	2.54
Paper and printing	Chemical pulp	1.40	0.98
	Mechanical pulp	0.91	0.64
	Paper	21.85	20.34
	Recovered fibres	15.86	15.29

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7 Summary and Conclusions

7.1 Introduction

The mitigation of climate change is one of the most important challenges of this century and the next two decades decisively influence whether we succeed in it. With energy use being the single strongest contributor to GHG-emissions, the switch to fossil-free energy carriers is a necessary and powerful measure to improve the likelihood of success. Therefore, reshaping the energy system both on the supply- and on the demand-side is a focus for climate change mitigation policies. Renewables have been strongly penetrating electricity supply during recent years in many countries. On the demand side, however, very heterogeneous structures exist that slow down the transition to a decarbonized society. Especially in the industry sector, fossil fuels form the backbone of energy use, accounting for 87% of fuel use in 2016 in the European Union [1]. With national, European and international ambitions to reduce GHG-emissions until 2030 ranging from 40% (EU[87]) over 55% (Germany) to 64% (IPCC[88]) compared to 1990, the need for immediate action in the industrial sector is apparent. In 2017, the industrial sector in Germany accounted for 196 $Mt_{CO2\text{-}eq.}$, and thus for about 22% of the national inventory [2,3]. On the European level, the industrial emissions (2017) amounted to 802 $Mt_{CO2\text{-}eq.}$ and about 19% of the inventory (4333 $Mt_{CO2\text{-}eq.}$) [4,5].

Deep decarbonisation of the industrial sector is necessary by 2050; however, this transformation process takes time, as large industrial processes require innovative low-carbon processes [6], which are currently not available. Meanwhile, the concept of a carbon budget demands the immediate reduction of GHG-emissions. Therefore, the reduction of emission intensity in existing industrial processes is important in the short- to medium-term. The replacement of fossil fuels by other energy carriers is an immediately available option to reduce emissions. The process of doing so is called fuel switching or inter-fuel substitution. This thesis shows that fuel switching can play a major role in achieving 2030 climate targets in the industrial sector and contribute to the transition towards a long-term carbon-neutral economy.

In principle, three types of fuel switching can be distinguished, based on the required effort and the degree of change to the core production processes. First, gradual fuel switch with limited technological change (e.g. change of burners in steam generation to use different fuels or allow flexible fuel use). These changes can happen fast as they are not tied to reinvestment cycles. Second, modernisation of larger parts of the production process and infrastructure usually carried out in modernisation cycles of five to ten years. Third, fuel switch measures that drastically change the

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[87] Entire economy, no sectoral targets defined. The new European Commission indicated that the target could be increased to 50% reduction. The emission trading target which covers larger parts of industry (but also energy supply) requires to reduce emissions by 43% in 2030 (compared to 2005).

[88] 45% reduction based on 2010, virtually distributed to Germany's industry sector. No legally binding target has been set on this level of detail.

production process and the applied technologies, e.g. the switch from coke-based to hydrogen-based ironmaking. These fuel switch measures are often strategic decisions, as they determine the production process for decades. The innovative, low-carbon production processes currently discussed are not ready to enter the market and it is thus unsure whether they can contribute to GHG-emission reduction until 2030. This thesis thus focuses on the first two fuel switch types. It creates a model to show how price signals and regulatory actions can incentivize fuel switching. As a result, it supplies a tool to improve model-based policy advice in the field of energy system analysis.

Informing policy-makers and the public with scientifically sound and transparent insights is a key enabler for responsible decisions. Yet, energy systems are complex and statements about the future can only be made under 'deep uncertainty' [7]. To describe these systems and derive robust knowledge about the impact of policy measures, energy system models are used. They represent the reality in simplified mathematical equations and thus make it accessible to scrutiny of policy influence and societal change.

The application of energy system models to fuel switching in the context of the manufacturing industry is hampered by generally low data availability and the heterogeneity and complexity of the sector. Technologies are embedded in production systems and thus, modelling technological change needs to take limitations of specific industrial processes into account. In addition, as energy use and investment in energy conversion equipment touch economic interests, relevant data needed for an appropriate model representation are often kept secret from the public. In fact, the decision process regarding investments is considered a vital business secret. Since the decision for a specific technology includes the commitment to a specific energy carrier (or a limited range of them), both aspects have to be investigated together.

The starting point of this thesis is the insight that fuel switch in the industrial sector is both highly relevant for climate change mitigation and requires deep knowledge of the involved processes, economic context and behavioural aspects. In current energy system models covering the industrial sector, these elements are, in principle, already present: Economic aspects form the basis of fuel switch considerations and are considered in all models (e.g. PRIMES, NEMS [8,9]). Technical barriers require detailed knowledge of the applied production processes and are thus less commonly included (e.g. *SmInd* [10]). The behavioural influences on fuel switch decisions are the least researched ones, with the most advanced example being the CIMS model [11]. No currently applied model investigates fuel switch in an integrated approach, combining these aspects. To some degree, this is caused by the models' scope, which often extends to other economic sectors and thus limits the achievable level of detail. The main barrier to the inclusion of behavioural aspects in fuel switch models is however the lack of empirical data. There is thus a research gap in the description of fuel switch decisions in the industrial sector in energy system models; the integration of economic, technical and behavioural aspects in a common framework for policy advice.

The thesis thus aims to describe the process of fuel switching in a way that allows it to be used as integral part of an energy system model used for scientific policy advice. To achieve this, the intersection of economic interests, behaviour and technical requirements is investigated. This requires the generation of empirical data on fuel switch decisions. The main research question is therefore:

"*How are fuel switch decisions made in the energy-intensive industry and how can they be integrated in a bottom-up energy system model to simulate energy carrier choice?"*

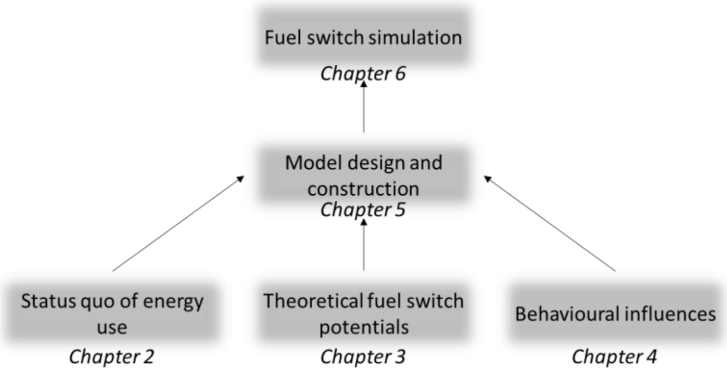

Figure 7.1: Abstracted thesis structure and information flow between chapters

Due to the scope and complexity of the topic, this research question is broken down to five sub-questions and investigated in five distinct parts as summarized in Figure 7.1. The first part describes the status quo of energy use in the industrial sector of the European Union (Chapter 2). By increasing the knowledge about the applications and temperature levels of heat and cooling demand in the sector, it lays the foundation for model-development that does justice to not only economic considerations, but also to technical aspects of industrial processes.

The second part estimates fuel switch potentials in the energy intensive sectors present in the EU ETS (Chapter 3) based on a literature review. It focuses on available technologies and fuel switch options that could be realized in the near future and thus contribute to GHG-emission reduction until 2030. It thus describes a technical potential from a bottom-up perspective, identifying important industrial processes and fields of action.

The third part (Chapter 4) supports the operationalization of fuel switch models by presenting the results of a survey among decision makers in German industry. The gathered data state preferences regarding steam generation technologies, which is, to the author's knowledge, novel for the industrial sector in the EU. These preferences enhance techno-economic scrutiny by behavioural influences and thus improve the ability of energy system models to represent real decision outcomes.

The fourth part describes the development of a fuel switch extension to the existing energy system model FORECAST (Chapter 5). This extension models fuel switch as the decision between discrete alternatives and thus enables competition among technologies and the energy carriers associated with them. In addition, this chapter operationalizes the model by informing it with behavioural parameters derived from a time-series analysis. It is shown that the model is capable to explain a good share of observed fuel switch in the past.

The last part (Chapter 6) condenses the previous chapters in a scenario analysis of practical fuel switch potential in the German manufacturing industry until 2030. It investigates, which conditions foster fuel switch and how it can support the German sectoral GHG-emission reduction targets for industry.

The respective sub-research questions are:

1. What is the current use of energy in industrial processes in the EU28 and what is a meaningful differentiation of energy use for energy carrier choice? (Chapter 2)

2. Which fuel switch measures in important industrial processes in the EU ETS are discussed in literature and how do the existing potentials relate to emission reduction targets? (Chapter 3)

4. How do energy carrier preferences in industrial steam generation influence energy carrier choice and how can an energy system model include them? (Chapter 4)

3. How can a bottom-up energy system model describe fuel choices in energy-intensive industries and how can it be parametrized? (Chapter 5)

5. Which economic incentives are necessary to support fuel switch to achieve mid-term climate targets, considering economic, technical and behavioural influences? (Chapter 6)

7.2 Summary of results

This section summarizes the main findings of the individual chapters and presents their main conclusions.

Chapter 2 investigates the status quo of energy use in the energy-intensive industries of the member states of the European Union and Norway, Switzerland and Iceland (EU28+3). It starts from the official energy balance of the statistical office of the European Union and disaggregates these data into end-use balances. By end-use we understand the application of the energy use (space heating, process heating, cooling) and the temperature level. It applies the energy system model FORECAST to distribute the energy demand on a subsectoral level to industrial processes. This bottom-up approach allows assigning process-specific properties to the energy demand, e.g. the applied technologies, temperature levels and applications. The model results deliver a concise overview of the status quo of energy use and thus offer new insights about important fields of action. It thus combines the data it is supplied with into a comprehensive picture, allowing further analysis. The results of this chapter thus generate a basis for further work on the modelling of fuel switch measures.

The approach delivers comparable results for individual countries, as the same methodology is applied to all of them. At the same time, the results match the official energy balance. The chapter includes an investigation of the fit to the energy balances and selected national end-use balances. It shows that the bottom-up approach works best for countries with a high overall energy demand and broad industrial structure, as uncertainties on individual processes do not influence the results too much in these cases. Small countries can show high deviation in the bottom-up calculation, as their industry is often composed of a number of smaller and heterogeneous subsectors. In contrast, larger countries often include a number of well-defined energy intensive processes, e.g. iron and steel industry. The smallest 20 countries only account for about 15% of the heating demand. However, while not as relevant for the EU28 as a whole, this shows that the investigation of individual countries requires additional data on their industrial structure.

Main findings of the chapter include the temperature distribution of heating and cooling in the EU28+3:

- **High temperature heat (above 500°C)** accounts for 45% (1035 TWh) of heating demand in the EU28 (2315 TWh); of this, three subsectors (iron and steel, basic chemicals, non-metallic minerals) use 96%. They combine the production of products with high energy-intensity and production volume such as iron and steel, ammonia, ethylene and cement clinker.
- **Steam demand in the range between 100°C and 500°C** (707 TWh) is mostly used in the paper and food industries, but also in a heterogeneous energy balance category 'other industry', which was not investigated further.
- **The temperature range theoretically accessible by low-temperature technologies (100°C - 200°C)** such as solar thermal systems, heat pumps and district heating amounts to 760 TWh.

- **Below this temperature**, space heat accounts for 346 TWh. Space and process cooling uses 100 TWh, of which cooling between 0°C and 15°C accounts for almost 50% (46 TWh).

This result is enhanced by an analysis of important processes and their temperature profile. The top five processes in terms of final energy demand (blast furnace, paper, ethylene, rolled steel and clinker calcination) together account for about 1000 TWh, almost half the industry's heating demand.

A country-wise evaluation of the temperature profiles shows that large countries (Germany, Italy, France, Spain, Netherlands, Poland, with the exception of United Kingdom) show similar shares of high temperature heat use (between 40% and 50%). These countries also rely heavily on fossil fuels, with around 70% of the process heat demand satisfied with natural gas and coal. Especially high-temperature heat is supplied with fossil fuels. This is also close to the EU28's share and indicates that large countries, for example Germany, can serve as proxy for the EU28 in high temperature range. Larger differences exist in the temperature range of 100°C - 200°C and below 100°C. The industrial structure of individual countries is visible in their temperature distribution (e.g. 100 °C - 200°C process heat use in the paper industry of Finland and Sweden).

The research sub-question "*What is the current use of energy in industrial processes in the EU28 and what is a meaningful differentiation for energy carrier choice?*" is therefore answered as follows: The current energy use of the EU28's industry is characterised by a high share of fossil fuels. High temperature process heat in particular utilizes high shares of fossil fuels, but also electricity (e.g. for the production of electric steel). Biomass is mainly used in low to medium temperature ranges. Temperature levels are an appropriate way to differentiate process heat demand. They yield meaningful differentiation regarding the applicable technologies. In addition, individual industrial processes must be considered when investigating fuel switch.

The value added of the work exposed in this chapter is that - with its approach on a process-level -, it delivers a so far unique level of detail and forms the foundation to evaluate fuel switch in industry. It thus sets the foundation to support researchers and policy-makers alike in identifying opportunities and fields of actions for energy efficiency and fuel switch, for example by revealing potentials for technologies with temperature restrictions like heat pumps. The work focusses on the national level. Future work evolves towards analysis on regional or even site-level, as questions on energy distribution and infrastructure gain importance. *The following chapters describe how the work done in this thesis extends the energy system model FORECAST with a fuel switch model. The thesis enables FORECAST to develop consistent scenarios of fuel switch in industry; including price sensitivities based on empirical data. It thus offers the ability to investigate the effect of policy measures better than previous models.*

Chapter 3 analyses fuel switch options in selected processes of basic material industries and crosscutting applications. It applies a mixed bottom-up/ top-down approach to estimate the total fuel switch potential of industries present in the European Union Emission Trading System (EU ETS). The EU ETS comprises the energy intensive industries and thus those with the highest impact on emissions from energy use. At the same time, the majority of process-related emissions is included in the EU ETS. The chapter focuses on the most important sectors based on their total emissions: refineries, iron and steel, non-metallic minerals (cement, lime, glass and ceramics), paper and basic chemicals. Together, these sectors account for 95% (547 $Mt_{CO2\text{-}eq.}$) of the EU ETS emissions, 64% of the (direct) industrial EU28 emissions in the EU ETS [12] and 75% of the final energy demand of EU28's industry [1].

The investigated processes' energy use is, as of today, dominated by fossil fuels. Natural gas and coal (including coke) account for 46% of the final energy demand. The remaining 54% consist of electricity (27%), oil (9%), renewables (7%) and others (11%). With the focus on emission reduction in the industry sector, the chapter analyses fuel switch options towards biomass and electricity. We do not consider switching from coal to natural case as sustainable, as this would only distract from reducing emissions to close to zero which is required in a 2050 perspective[89]. This is motivated by our knowledge of climate change and the understanding that the use of fossil fuels must cease in the first half of this century to reduce the extent of global warming. Furthermore, reduction of greenhouse gas (GHG) emissions must be strongly reduced already until 2030 to stay on a path below 2°C and, if possible, limit global temperature rise to 1.5°C. For this reason, the chapter focuses on technologies that are either directly available or may have a relevant impact until 2030. This requires restricting the analysis to technologies with a technology readiness level (TRL[90]) of 6 or higher. This means that the technologies are at least validated in relevant environments and are fit for demonstration plants. This still requires ambitious development to reach market-readiness by 2030.

Results show that considerable potential for fuel switch towards biomass and electricity exist in several industries. Among the most influential measures are the use of biogenic fuels in lime and clinker production (57 $Mt_{CO2\text{-}eq.}$), biomass use in blast furnaces and shift towards electric arc furnaces (EAF[91]) with 35 $Mt_{CO2\text{-}eq.}$, the replacement of purchased fuels in refineries (42 $Mt_{CO2\text{-}eq.}$) and the use of biomass or electricity in further steam systems and furnaces (28 $Mt_{CO2\text{-}eq.}$). Combined, these and other options sum to a mitigation potential of 184 $Mt_{CO2\text{-}eq.}$ in 2030 (Figure 7.2). This is a reduction compared to 2016) by 34% and puts the emission reduction pathway in line with 1.5°C scenarios that

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89 This kind of fuel switch is possible within the model developed in this thesis, but not investigated in particular.

90 According to [13]:
TRL 1 – basic principles observed
TRL 2 – technology concept formulated
TRL 3 – experimental proof of concept
TRL 4 – technology validated in lab
TRL 5 – technology validated in relevant environment
TRL 6 – technology demonstrated in relevant environment
TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified
TRL 9 – actual system proven in operational environment

91 The shift to scrap-based EAF is both a circular economy action (as recycled steel is used as raw material) and fuel switch. In addition, it aligns with possible long-term pathways towards hydrogen-based steelmaking.

require a reduction by 55% compared to 1990. Yet, emissions of about 275 $Mt_{CO2\text{-}eq.}$ remain unaffected by the discussed fuel switch options.

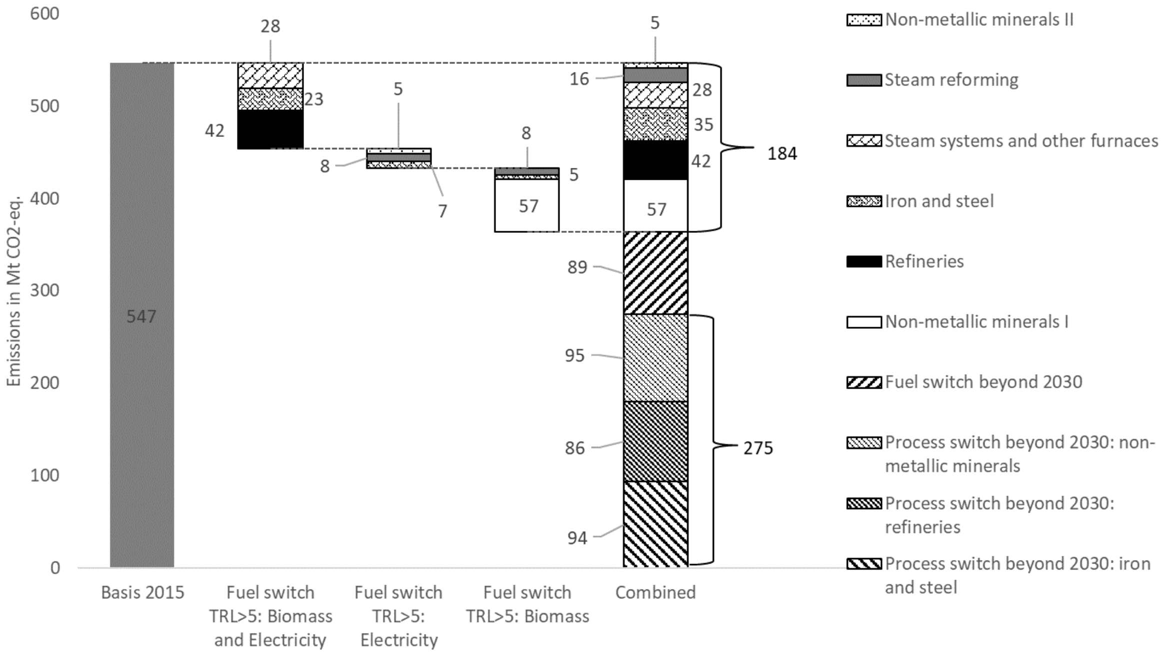

Figure 7.2: Emission reduction potentials by fuel switch measures discussed in Chapter 4 and remaining emissions;

Both focused mitigation options, renewable electricity generation and sustainable biomass, are limited. Estimates on the available sustainable potential of biomass and renewable electricity in the European Union show that long-term potentials (2050) exist to supply the described fuel switch. However, the availability of those energy carriers in 2030 in the required quantities is questionable, as their development depends on political commitment. With an assumed realisation of 50% of the 2050 potential until 2030, the available supply of sustainable biomass and renewable electricity sources would not suffice to cover the additional demand generated by the fuel switch options investigated. The main conclusion of this chapter is thus, that fuel switch has indeed an important role in climate change mitigation: the industry sector has technical options to switch to a less GHG-intensive heat supply. Key enabler to realise these options is, however, the competitive availability of electricity and biomass. What this means and how competitiveness to fossil fuels can be created, is subject of the next chapters.

The research question is therefore answered as follows: Large fuel switch options exist in all subsectors of the basic materials industry. Especially the use of biomass and electricity to replace fossil fuels in iron and steel, chemicals and non-metallic minerals show high potential. All of these potentials combined, could suffice to reduce GHG emissions according to 1.5°C global warming scenarios. Yet, fuel switch is but one measure and additional options must be investigated, e.g. energy and material efficiency, circular economy and innovative processes, to name a few. These have interactions and feedbacks.

In this chapter, only the technical potential is investigated. However, the literature review also shows clearly that economic barriers are the main reason why important potentials are not realized. Most importantly, high electricity prices compared to e.g. natural gas severely limit the attractiveness of process heat electrification. The identified potentials also do not account for investment cycles in industry[92]. Considering the limited timeframe (2030), natural stock turnover puts strict limitations on the achievable fuel switch. These two key points however govern decisively, whether fuel switch actually takes place or remains a potential. In the subsequent chapters, these questions are addressed.

The value added of this chapter is the collection, interpretation and quantification of fuel switch potentials scattered in sector- or process-specific literature. This chapter creates a comprehensive overview of currently discussed fuel switch measures in energy-intensives processes present in the EU ETS and presents an estimate of the combined technical potential. It thus delivers the basis for the economic evaluation of these potentials and for the integration in energy system models, which is carried out in the following chapters.

Chapter 4 lays the foundation to include behavioural aspects in a fuel switch model. It derives 'stated' preferences for steam generation technologies via a survey. We focus on steam generation as a large, comparatively homogeneous end-use in industry. Stated preferences, which are reactions to theoretic situations, have the advantage to include 'what if' aspects, since the survey participant is confronted with theoretic alternatives that do not necessarily exist yet or are not relevant in the market yet[93]. Their disadvantage is the possible lack of commitment, as the choice does not yield any real consequences.

In this particular case, we asked decision makers in German companies that operate steam generators about the perceived attractiveness of presented steam generation options. The participants worked in the subsectors 'food processing', 'chemical and pharmaceutical production' and 'paper and card-board production'. The sample distribution was representative for the company distribution of the investigated subsectors. The participants were confronted with three sets of steam generators, each set containing three systems. Within this selection, the participants were to determine the attractiveness of the systems. This attractiveness can be translated to monetary values by cross-referencing the steam generation costs.

The evaluation of the answers yielded significant results in all investigated attributes (steam generation costs, energy carrier and technical availability). This means, all of them are likely to be

92 In the case of steam systems, a stock turnover of 50% until 2030 is assumed.

93 However, they must be close to reality or at least plausible in order to receive meaningful results.

relevant for system choice. In particular, the energy carrier attribute played a strong role in decision-making[94]. Coal and oil are rated significantly less attractive than natural gas and biomass.

Main conclusions from these results are that energy carrier preferences exist and are significant. They are thus a necessary part of fuel switch considerations. The research question can therefore be answered like this: Energy carrier preferences significantly influence the choice of steam generation technologies and they go beyond mere price differences.

The value added of this chapter is the quantification of preferences for fuel switch in steam systems. They give a point of reference for future research and application in energy system models. The connection to generation costs allows integration in bottom-up energy models that calculate costs, e.g. based on capital and operation expenditures. The results can thus be operationalized to increase the price responsiveness of models. From a societal perspective, the increased knowledge about system preferences can support targeted policy-design to incentivize fuel switch to low-carbon technologies.

Chapter 5 develops a model extension to the existing bottom-up energy demand simulation model FORECAST. This extension addresses fuel switch in high-temperature processes and integrates technical, economic and behavioural aspects, building upon the technical potentials identified in Chapter 3. It thus aims to give a comprehensive account of achievable fuel switch under varying framework conditions. Special considerations are given to price sensitivities, the preferences of market participants and technical restrictions that exclude energy carriers from certain applications. These considerations make use of the temperature profiles derived in Chapter 2, focusing high temperature processes as those are of high relevance in the EU28. This chapter additionally generates 'revealed' preferences for industrial furnaces via a time series analysis. It thus strengthens the empirical basis for fuel switch modelling, complementing the data gathered for steam generation in Chapter 4.

The model approaches fuel switch decisions from the perspective of an idealized decision maker within her specific environment. The idealization consists of the assumption, that the decision maker is a representative of its group. A group is defined by industrial subsectors (and countries)[95]. Therefore, the decision maker is not a real person or institution, but representative that makes the same decisions as the aggregate of all market participants. This results in a distribution of market

94 A cost increase of 1 €ct/kWh reduces the attractiveness of a system by 0.410 points and one percent of downtime by 0.383 points. The change of the energy carrier to natural gas or biomass from coal increases attractiveness by 1.802 points, from oil by 0.926 points. Put in monetary terms, this equals a cost increase of 2.26 €ct/kWh for oil and 4.40 €ct/kWh for coal. Given the possible cost range of 4 - 10 €ct/kWh, this is a strong effect.

95 For example, the iron and steel industry in Germany chooses different energy carriers than that in Italy. The different shares of the primary and secondary production route can in part, explain this. The non-metallic minerals use different energy carriers than the paper industry due to process-specific properties (possibility to use waste in clinker burning, biomass residues in pulp production).

shares of the available technologies. The decision process is based on the theory of discrete choice, in which discrete options are presented as alternatives. The competition between these alternatives constitutes price sensitivity.

However, while economic influences have a major influence on energy carrier choice, additional parameters define the outcome of the model. The novelty of the work consists in the identification of preferences for energy carriers[96], energy-intensive subsectors and countries included in the Eurostat energy balances. These preferences modify the economic evaluation of the energy carriers to define an attractiveness, or, in model terms, utility. This attractiveness accounts for the observation that prices alone cannot explain the energy carrier use. The preferences are derived from time series analysis. In this approach, the developed fuel switch model is applied backwards to an observed period for which both the outcome (energy carrier shares) and input (prices) are known. It is fitted with a least-squares-approach against the observed developments in this period. The resulting parameters define the decision process and most importantly, the price sensitivity of the decision maker. The fuel switch model is thus capable to reflect the reaction of the subsectors to price changes. Other influences on the energy carrier choice, for example existing infrastructure and process technologies on-site or long-term delivery contracts, are abstracted in model parameters that govern the reaction to price signals. These model parameters represent the subsectors' preferences.

The 'revealed' preferences reflect the perceived attractiveness in the given period. They are thus well suited to simulate business-as-usual developments but lack information on reactions to drastic changes, e.g. price shocks or strong policy-driven influences. For the purpose of policy advice, especially on the pressing matter of climate change, the best possible assumption is that the preferences remain constant. At the moment, it is unclear how these preferences change over time. While the simple availability of these preferences is already an improvement, further work needs to deepen the knowledge about the industry's reaction to disruptive changes.

The research question "*How can a bottom-up energy system model describe fuel choices in energy-intensive industries and how can it be parametrized?*" is answered like this: The implementation of a discrete choice model for fuel switch in a bottom-up energy system model requires the definition of appropriate aggregates for both energy carriers and decision makers. The discrete choice approach creates a competition between energy carriers and the attractiveness within this competition is influenced by price signals, technical aspects and group-specific preferences. The parameters of the model can be derived from time series analysis ('stated preferences') with a satisfying coefficient of determination (average of .64). Small countries require special attention as statistical errors impact the results stronger. Overall, a sophisticated bottom-up process structure is needed to represent fuel choice in industry.

96 For methodological reasons, some energy carriers are grouped, for example, several solid fuels are grouped as 'coal' (see Chapter 2).

The value added of this chapter consists of the generation of quantified preferences for energy carrier choice in high-temperature processes. These preferences are applied in a discrete-choice fuel switch model as an extension to a bottom-up energy system model. In this combination, they create a price-sensitivity of fuel switch and allow the evaluation of economic and political influences on energy carrier use. The developed model includes technical aspects on process level and behavioural and economic aspects on subsector level. It is the first model to consider these three aspects in an integrated approach. It thus supports policy advice and research on fuel switch with a closer representation of reality than previously available.

Chapter 6 investigates the role of price signals on fuel switch in general and towards biomass and electricity in particular. It combines the results of the previous chapters to form comprehensive fuel switch scenarios. It thus comprises high-temperature process heat in furnaces (see Chapter 5), steam generation (see Chapter 4) and hot water and space heating[97], implementing the heat demand structure generated in Chapter 2. It supplies fuel switch options identified in Chapter 3, among them the use of biomass in blast furnaces and cement production as well as electrification potential in steam generation. The model developed and parametrized in Chapter 5 is applied to high-temperature process heat demand. The fuel switch decisions in steam generation are influenced by the preferences identified in Chapter 5.

The scenario analysis includes four scenarios, in which different policy instruments are investigated (Table 7.1). First, a base scenario without any subsidies, CO_2-price, faster technology stock exchange or regulatory measures[98]. Second, an investment scenario with no subsidies on process heat generation but on their investment (CAPEX-centred). Third, a replacement scenario with a higher rate of steam and furnace exchange, leading to a faster transition. Fourth, a regulation scenario, in which, on top of the replacement scenario, new fossil-fuel steam installations are banned and the technology exchange is increased even further.

97 Building upon the work of Biere [14].

98 In subsequent variations, subsidies on electricity use for process heat generation (OPEX-centred) and a price on CO2-emissions is added.

Table 7.1: Scenario structure Chapter 6

	Scenario	Base	Investment	Replacement	Regulation
Framework	Production activity	Depending on the product: Slow growth or stagnating			
	Energy carrier prices	Following historic trends			
Measures	CO2-price	25 EUR/t_{CO2} in 2020, linear growth to 50 EUR/t_{CO2} in 2030			
	Subsidies	Yes	No	Yes	Yes
	Investment support	No	100%	No	No
	Early replacement	No	No	75% of technical lifetime 2025-2030	75% of technical lifetime 2025-2030
	Fossil ban new installations	No	No	No	After 2025
	Rational choice	50%	50%	75%	75%-100%

All policy measures are designed to increase the attractiveness of low-GHG technologies, or decrease those of GHG-intensive ones. They thus support the transition to less GHG emissions. In this case, we select the German 2030 target for the industry sector as end point of the model. The Chapter thus investigates how fuel switch measures can contribute to this target and what policies may support it.

The strength of the policies (CO_2-price and OPEX-subsidies) are varied in a series of model runs and their effect on GHG-emissions is measured. Results show that without increased technology exchange, even high subsidies (virtually free electricity for process heat purposes) and CO_2-prices (300 €/$t_{CO2\text{-}eq.}$) do not suffice to achieve the German 2030 targets for the industry sector on their own. They do also show that investment subsidies are unfit to increase the transition speed, as the capital expenditure are almost negligible compared to operating expenses, in particular energy costs. To reach the target corridor of 140 $Mt_{CO2\text{-}eq.}$ to 143 $Mt_{CO2\text{-}eq.}$ in 2030, an increased technology exchange is needed. A ban on fossil fuels may lower the required economic incentives. Finally, even highly ambitious policies supporting fuel switch do not enter a pathway compatible with an estimate for 1.5°C global warming compatible emission reductions (Figure 7.3).

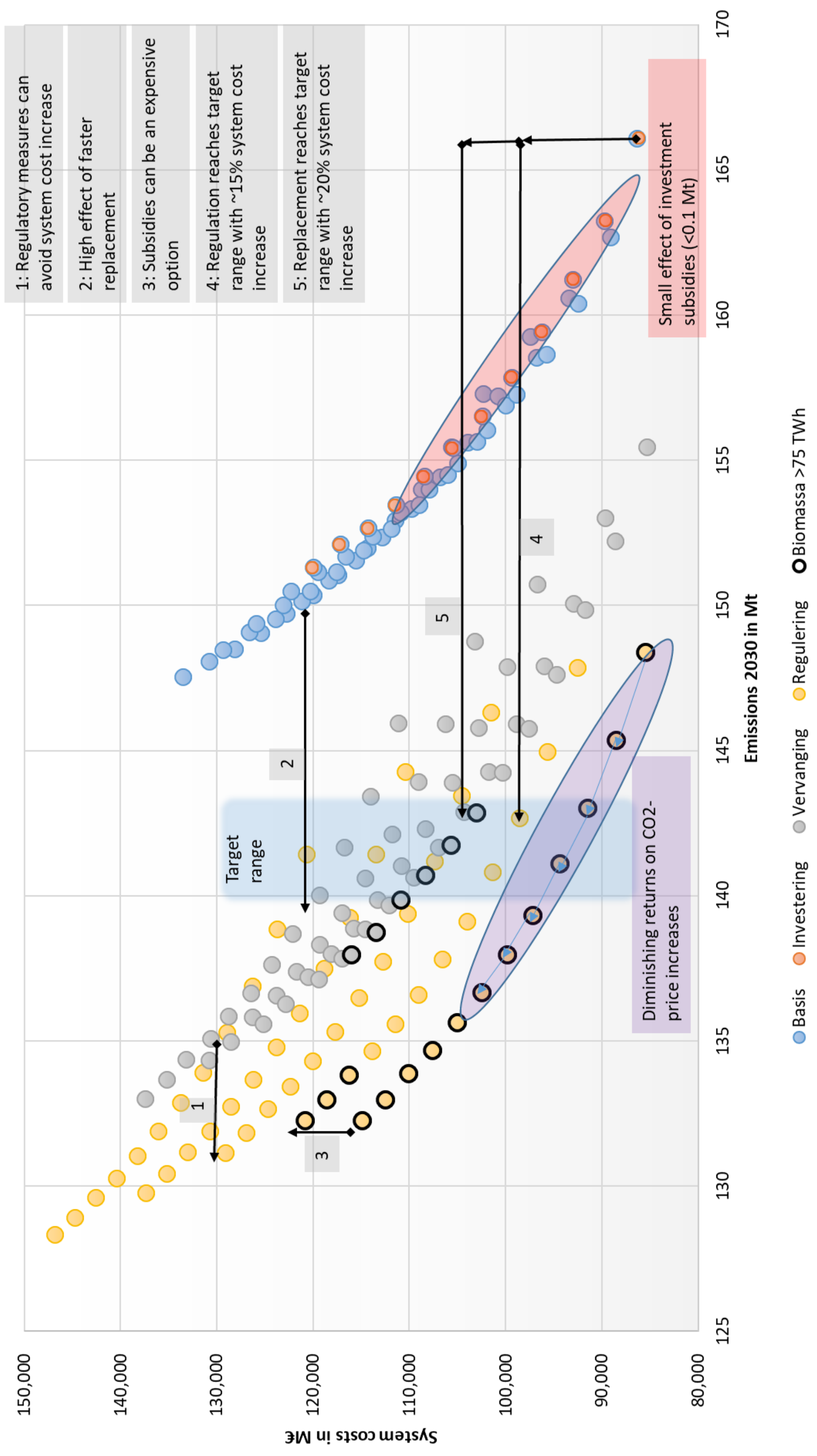

Figure 7.3: System costs over GHG emissions for variations of electricity subsidies and CO2-prices

One of the reasons for the limited impact of fuel switch are emissions not accessible by fuel switch: Coke use in blast furnaces, by-product gases in refineries and process-related emissions, e.g. in cement production. These emissions account for almost half the industry's emissions in the EU ETS and a similar share of Germany's industrial emissions. Due to this almost incompressible share, the price sensitivity of the overall emissions is limited and strong incentives and regulations are necessary to achieve fast emission reduction. Additional measures, such as demand reduction and material efficiency thus seem necessary already until 2030.

The analysis chooses a technical approach, separating economic incentives and technology exchange rates. It is plausible to assume that high subsidies and CO_2-prices trigger an increased replacement of old installations. Even investment subsidies might be helpful in this regard, if supported by policies influencing operating costs. The research question is answered like this: To support fuel switch in line with mid-term climate targets (exemplary for the case of Germany's industry target in 2030) two aspects must be considered: First, there must be a business case for low-GHG technologies. The process heat generation costs must be below fossil fuel fired alternatives, which seems, with current and foreseeable energy carrier prices, only possible with government intervention. For example, the exemption from state-imposed electricity price components for industry already applied for selected industries creates a range of about 11 €ct/kWh. Second, even when attractive low-GHG technologies are on the market, the speed of stock turnover observed in the previous decades does not suffice to phase out fossil fuels fast enough. The remaining 10 years until 2030 thus call for immediate action and increased effort. It is necessary to replace process heat installations before their technical lifetime expires. In consequence, each fossil fuel fired system installed from now on is a step in the wrong direction and probably a stranded investment. Additionally, the large amount of emissions unaddressed by fuel switch show that measures must be taken to introduce new production processes and replace the sources of so far rather incompressible emissions: blast furnaces, refineries, process-related emissions. This is not only necessary for deep emission reductions until 2050, but would also lower economic pressure on the price-sensitive emissions investigated in this chapter.

The value added delivered by this chapter is the quantification of two heavily discussed GHG-emissions reduction measures (electrification and CO_2-pricing) in an integrated model approach. The applied scenario analysis reveals major levers to facilitate fuel switch (stock exchange and operational expenses). The reactions to price signals support policy design (e.g. definition of non-ETS CO_2-prices in Germany). The methodology of scenario analysis allows addressing uncertainties in the framework data (e.g. energy carrier prices and economic growth). The chapter thus contributes to ongoing and highly relevant societal discussions with evidence-based insights.

7.3 Conclusions

The main conclusion of this thesis is that fuel switch is an important measure to succeed in one of the greatest challenges of this century, the mitigation of anthropogenic climate change. It offers potentials that can be harnessed in the coming decade (Chapter 3 and 6). From a technical point of view, demand-side measures such as increased use of biomass is feasible in many current processes. Similarly, electrification of process heat demand both in high- and mid-temperature ranges is possible. High impact examples include the gradually injection of biomass in rotary (cement), shaft (lime) and blast (iron) furnaces as well as electricity-based steam generation. Yet, large emission sources remain unaffected by fuel switch and must be addressed differently (Chapter 3). For steam generation, preferences towards less emission-intensive technologies exist and they can support the transition away from fossil fuels, if the economic conditions allow it (Chapter 4). In high-temperature industrial applications, which account for 45% of the EU28 industrial heating demand (Chapter 2), the thesis revealed a substantial price sensitivity, showing that economic incentives for fuel switch can be effective (Chapter 5). These incentives must be very high, but supporting measures such as faster stock exchange substantially reduce the required economic pressure and/or subsidies (Chapter 6).

While the discussed fuel switch options are technically available, they are economically challenged. Electricity is not competitive in industrial steam generation and restricted to special applications in the high-temperature range. In general, natural gas is the more attractive energy carrier. In the current economic environment, strong policy influence would be needed to incentivize a switch to direct use of electricity for process heating purposes. The main motivation of the developed model is the goal to determine feasible and plausible transformation paths towards sustainable industrial energy demand. Chapter 4 and 6 showed that considerable fuel switch options contributing to this goal exist. However, they are often not competitive due to high energy carrier prices compared to fossil fuels. The supply of competitive low-emission fuels and renewable electricity is thus one of the major prerequisites for fuel switch. Chapter 6 showed that subsidies on the electricity price of 5 €ct/kWh in the example of Germany would suffice to incentivize sufficient electricity use (increase of ~15 TWh for process heating purposes compared to the base case) to reach a solution compatible with industrial 2030-targets (reduction of GHG-emissions by 50% compared to 1990). However, substantial electricity use (roughly doubling current electricity use for process heating to 130 TWh) requires higher subsidies (up to 20 €ct/kWh), effectively delivering electricity at or below natural gas prices.

Chapter 6 shows that the technology rate of stock exchange is an important factor to reach mid-term climate targets. Stock exchange is often hampered by long lifetimes and reinvestment cycles in industry. Synthetic fuels on the other hand could replace fossil fuels without the need for technical change on the demand side. They could thus circumvent a lengthy stock exchange especially in industrial furnaces. It is however yet unclear, how they can be produced in sufficient quantities and at competitive prices. Additional uncertainties include the sustainability of such solutions in the light of land use change, perpetuated import dependencies of Europe, additional environmental impacts.

In addition, there are discussions about the economics of synthetic fuels compared to CCS-enhanced natural gas use, especially regarding the carbon cycle and its logistics.

This thesis identified and quantified large emission sources that cannot be addressed by fuel switch. The use of a certain share of coke is, in modern blast furnaces, necessary and blast furnaces are required to supply the high quality steel grades demanded by modern societies. Replacing coke (and coal) thus means replacing the blast furnace and in turn an entire energy-'ecosystem'. The associated decisions are of a strategic nature and not accessible with the fuel switch model developed in this thesis. While demonstration plants for alternative production processes (e.g. hydrogen based direct reduction) are in construction, their large-scale deployment is not considered here until 2030[99]. Moreover, process emissions from a variety of processes are not influenced by fuel switch. The most relevant sources is limestone calcination, applied in cement and lime production. With CO_2 being a necessary waste product of clinker burning, material efficiency, sufficiency and new cement types are the most promising options for GHG-emission reduction in this sector. All of these options have substantial feedbacks to all sectors of society. While this thesis does not consider these, the approach applied in this thesis provides a starting point to consider the options present in the industry sector e.g. in coupled model systems.

Carbon capture and storage (CCS) is a relatively convenient and almost immediately available option. Given the limited timeframe to mitigate climate change, it might even be a necessary one. However, based on the work done during the creation of this thesis, the author believes that it should merely be a bridge or emergency technology and not the central pillar of GHG-emission reduction efforts. Highest effort should focus on avoidance. As a supportive element however, CCS may find use in selected applications. Process-related emissions in industry for example are not addressable by fuel switch. If they cannot be avoided by other means, e.g. a change of raw material, they are likely to consume any GHG budget left in 2050 (for example with a 95%-reduction target). The most relevant processes in this regard are lime and clinker production, which are thus a prime example for the application of CCS [16]. So are other GHG-emission intensive processes like iron and steel production, refineries and some basic chemicals [17].

From a methodological point of view, this thesis shows that it is possible to include a discrete choice approach in a bottom-up energy model of the industrial sector. This method was before mostly applied to consumer-centred topics as private and public transportation or to industrial applications with limited scope. In addition, the thesis applied two approaches (revealed and stated preferences) to inform the model with parameters and thus to operationalize them. These preferences were previously not available and the thesis shows that they can be acquired both on a national and European level with reasonable effort. This is a requirement for the application of the approach. Widening the picture, the thesis and the work done during its creation contribute to policy advice regarding energy

99 Although opinions on the feasibility of their deployment differ [15]; first pilot plants are envisioned until 2030 or even 2025. However, the impact on the European GHG-emissions likely becomes relevant later.

transition, climate change mitigation and related policymaking by quantifying the GHG-emission reduction potential of selected policy measures (energy-carrier specific subsidies and CO_2-pricing).

7.4 Recommendations for further research

This thesis focused energy-intensive industries and the processes with the highest emissions, as those are the most relevant for large-scale emission reduction. While several smaller processes were also included in the analysis, the effort should be increased to represent their properties and potentials in more detail. This is especially true when their sectors have strategic importance in deep emission reduction scenarios. Examples include food production, textile, wood production, mining (due to land use), machinery and vehicle production (due to their importance in the German and European economy). These processes are usually heterogeneous and numerous, which creates additional challenge for modelling. So does the addition of site-specific information, which may reveal additional challenges to and opportunities for fuel switch. Further analysis may then include new business models and organisational structures (e.g. energy contracting, small energy grids, waste-heat networks) and their impact on fuel switch potentials.

The potential for fuel switch in existing installations is substantial and it is able to deliver fast emission reductions. Ultimately, these are not enough to deliver emission reductions required until 2050, though. It is therefore clear that after 2030, deep emission reductions must be achieved with new processes that require higher effort and replacement of entire production chains. This includes the direct use of electricity, the utilization of hydrogen (as energy carrier and feedstock) and CCS in selected applications. As of now, robust economic data on many of these technologies are lacking[100]. They are thus difficult to include in endogenous model calculations, e.g. as competition to conventional production technologies. The operation of first demonstration plants in the coming decade might present the opportunity to do this. Yet, the interaction of short- and long-term measures is unclear: Do the short-term options support the transition to new processes or do they create new lock-in effects? The construction of roadmaps considering immediate action and the 2050-perspective may identify undesirable paths and question fuel switch potentials. Finally, the interaction with infrastructures is not investigated in this thesis, but is of increased importance for the use of grid-bound energy carriers such as electricity, district heat and natural gas.

The fuel switch described in this thesis is integrated in a sectoral bottom-up model. It confirmed, however, the widespread notion that the interaction of the economic sectors, especially the transformation sector, will be of substantial importance. An interaction of the different demand sectors and energy distribution and supply will be necessary to answer questions associated with deep emission reduction. The endogenous modelling of innovative processes requires the representation of new, and potentially dynamic, cross-sectoral material and energy flows as well. It influences the entire system and includes strategic decisions. Modelling those is not natural to the myopic approach

[100] With the best experiences in CCS [16] and direct electrification of steam systems but limited knowledge about the performance of innovative production processes [18]. The Innovation Fund [19] currently deployed by the European Commission may improve the data basis. Currently, projects to develop innovative production processes are being evaluated.

chosen for gradual fuel switch in this thesis. Further research must focus the 'service' of a product and allow for dynamic shifts of material flows and process routes.

In this thesis, model parameters (revealed and stated preferences) for fuel switch were derived that have not been available before. While they work and create plausible results, it would be beneficial to reproduce these results with different methodologies, taking into account more sophisticated quantitative analyses (revealed preferences). The selected period may be extended to include the effect of the economic crisis in 2008 to derive reactions to demand shocks on fuel switch behaviour. In addition, the thesis showed that the model parameters are less reliable for small countries of the EU28, which might also be improved with detailed analyses of those. The stated preferences may be extended by additional technologies and a higher number of participants, by focussing on more countries in the European Union. This could on the one hand allow analysing subsectoral-preferences, but also improve our understanding of market chances for e.g. high-temperature heat pumps, hydrogen and direct electricity use.

The 'wish list' presented in the previous paragraphs will not be fulfilled in a single model. Therefore, the interaction of models will increase. Efforts must be made to open the individual models to others and create transparent and versatile model interfaces. At the same time, the complexity of the models applied in policy advice would have to be reduced. It is an uncomfortable fact that the knowledge about the models applied for policy advice with high impact on the society is concentrated on only a few modellers and hard to disseminate. This could be helped by deliberately removing model parts that are not needed (in their full complexity) in regular intervals, thus focusing the core elements necessary to answer the respective research questions. In consequence, this could create a viable path to open source models and increase transparency and thus credibility, societal impact and applicability of energy system models and policy advice based on them.

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8 Samenvatting en conclusies

8.1 Inleiding

Het tegengaan van de klimaatverandering vormt een van de belangrijkste uitdagingen van deze eeuw en de komende twee decennia zullen van doorslaggevende invloed zijn op de vraag of we hierin slagen. Aangezien het energieverbruik de grootste bijdrage levert aan de uitstoot van broeikasgassen, vormt de overstap naar fossiele energiedragers een noodzakelijke en daadkrachtige maatregel om de kans op succes te vergroten. Daarom vormt de herziening van het energiesysteem, zowel aan de vraag- als aan de aanbodzijde, een aandachtspunt voor het beleid voor de beperking van de klimaatverandering. Hernieuwbare energiebronnen zijn de afgelopen jaren in veel landen sterk in de elektriciteitsvoorziening doorgedrongen. Aan de vraagzijde bestaan er echter zeer heterogene structuren die de overgang naar een koolstofarme samenleving vertragen. Vooral in de industriesector vormen fossiele brandstoffen de ruggengraat van het energiegebruik, goed voor 87% van het brandstofverbruik in 2016 in de Europese Unie [1]. Met nationale, Europese en internationale ambities voor het verminderen van de uitstoot van broeikasgassen tot 2030, variërend van 40% (EU[101]), meer dan 55% (Duitsland), tot 64% (IPCC[102]) in vergelijking met 1990, is de noodzaak voor onmiddellijke actie in de industriële sector duidelijk. In 2017 was de industriële sector in Duitsland goed voor 196 MtCO2-eq. en dus voor ongeveer 22% van het nationale inventaris [2,3]. Op Europees niveau bedroeg de industriële uitstoot (2017) 802 MtCO2-eq., ongeveer 19% van het inventaris (4333 MtCO2-eq.) [4,5].

Vergaande decarbonisatie van de industriële sector is noodzakelijk tegen 2050; dit transformatieproces vergt echter tijd, gezien het feit dat omvangrijke industriële processen innovatieve koolstofarme processen [6] vereisen, die momenteel niet beschikbaar zijn. Intussen vereist het concept van een koolstofbudget een onmiddellijke vermindering van de uitstoot van broeikasgassen. Daarom is de vermindering van de emissie-intensiteit in bestaande industriële processen belangrijk op de korte tot middellange termijn. De vervanging van fossiele brandstoffen door andere energiedragers vormt een onmiddellijk beschikbare optie voor het verminderen van de uitstoot. Dit proces wordt fuel switching of inter-fuel substitution (brandstofvervanging) genoemd. Dit proefschrift toont aan dat de overschakeling op andere brandstoffen een belangrijke rol kan spelen bij het bereiken van de klimaatdoelstellingen voor 2030 in de industriële sector en op lange termijn kan bijdragen aan de overgang naar een koolstofneutrale economie.

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101 Gehele economie, geen sectorale doelstellingen gedefinieerd. De nieuwe Europese Commissie heeft aangegeven dat de doelstelling kan worden aangescherpt tot een reductie van 50%. De doelstelling voor de handel in emissierechten, die betrekking heeft op grotere delen van de industrie (maar ook op de energievoorziening), vereist een vermindering van de uitstoot met 43% tot 2030 (ten opzichte van 2005).

102 45% reductie op basis van 2010, virtueel verdeeld over de Duitse industriesector. Er werd op dit detailniveau geen wettelijk bindend doel vastgesteld.

In principe kunnen drie soorten brandstofvervanging worden onderscheiden, op basis van de vereiste inspanning en de mate van verandering van de kernproductieprocessen.

Ten eerste, geleidelijke overschakeling op een andere brandstof met een beperkte technologische verandering (bijv. vervanging van branders in de stoomopwekking om andere brandstoffen te kunnen gebruiken of een flexibel brandstofgebruik toe te staan). Deze veranderingen kunnen snel plaatsvinden omdat zij niet gebonden zijn aan herinvesteringscycli. Ten tweede, modernisering van grotere delen van het productieproces en de infrastructuur, doorgaans uitgevoerd in moderniseringscycli van vijf tot tien jaar. Ten derde, brandstofvervangingsmaatregelen die het productieproces en de toegepaste technologieën drastisch veranderen, bijvoorbeeld de overschakeling van de productie van cokes naar de productie van ijzer op basis van waterstof. Deze brandstofvervangingsmaatregelen hebben vaak de vorm van strategische beslissingen, aangezien zij het productieproces decennialang bepalen. De innovatieve, koolstofarme productieprocessen die momenteel worden besproken, zijn nog niet klaar om op de markt te worden gebracht en het is dus niet zeker of zij tot 2030 kunnen bijdragen aan de vermindering van de BKG-uitstoot. Dit proefschrift richt zich dus op de eerste twee soorten van brandstofvervanging. Het creëert een model om aan te geven hoe prijssignalen en regulerende maatregelen een stimulans kunnen vormen voor het overschakelen op een andere brandstof. Het levert daarmee een instrument om modelgebaseerd beleidsadvies op het gebied van energiesysteemanalyse te verbeteren.

Het informeren van beleidsmakers en het publiek met wetenschappelijk onderbouwde en transparante inzichten vormt een belangrijke voorwaarde voor verantwoorde beslissingen. Toch zijn energiesystemen complex en kunnen uitspraken over de toekomst alleen worden gedaan met “aanzienlijke onzekerheid” [7]. Om deze systemen te beschrijven en robuuste kennis over de impact van beleidsmaatregelen af te leiden, wordt gebruik gemaakt van energiesysteemmodellen. Zij geven de werkelijkheid weer in vereenvoudigde wiskundige vergelijkingen en maken deze zo toegankelijk voor onderzoek naar beleidsbeïnvloeding en maatschappelijke verandering.

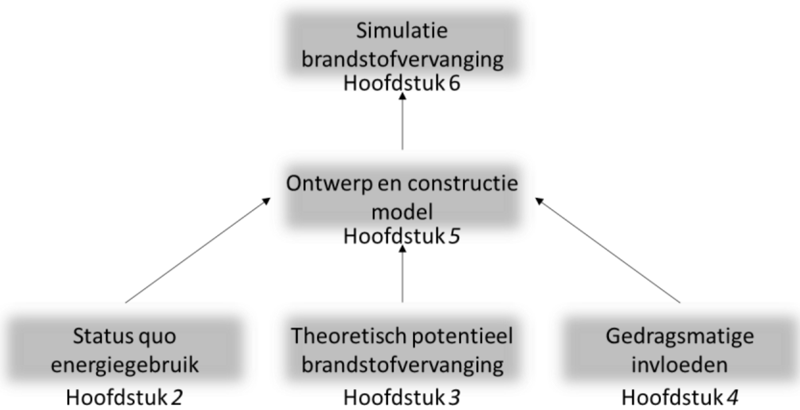
De toepassing van energiesysteemmodellen op de overschakeling op andere brandstoffen in de context van de verwerkende industrie wordt belemmerd door de over het algemeen lage beschikbaarheid van gegevens en de heterogeniteit en complexiteit van de sector. De technologieën zijn ingebed in productiesystemen en bij de modellering van technologische veranderingen dient dus rekening te worden gehouden met de beperkingen van specifieke industriële processen. Aangezien het energieverbruik en de investeringen in apparatuur voor energieomzetting economische belangen raken, worden de relevante gegevens die nodig zijn voor een passende modelweergave vaak geheim gehouden voor het publiek. In feite wordt het besluitvormingsproces met betrekking tot investeringen als een essentieel bedrijfsgeheim beschouwd. Daar de keuze voor een specifieke technologie het engagement voor een specifieke energiedrager (of een beperkte reeks hiervan) omvat, dienen beide aspecten samen te worden onderzocht.

Het uitgangspunt van dit proefschrift wordt gevormd door het inzicht dat de overschakeling van brandstof in de industriële sector zowel zeer relevant is voor de beperking van de klimaatverandering, als een diepgaande kennis vereist van de betrokken processen, de economische context en de gedragsaspecten. In de huidige energiesysteemmodellen voor de industriële sector zijn deze elementen in principe reeds aanwezig:

Economische aspecten vormen de basis voor de overwegingen inzake brandstofvervanging en worden in alle modellen (bijv. PRIMES, NEMS [8,9]) in aanmerking genomen. Technische barrières vereisen gedetailleerde kennis van de toegepaste productieprocessen en worden dus minder vaak opgenomen (bijv. *SmInd* [10]). De gedragsbeïnvloeding van brandstofvervangingsbeslissingen is het minst onderzocht, met als meest geavanceerde voorbeeld het CIMS-model [11]. Geen enkel actueel toegepast model onderzoekt brandstofvervanging door middel van een geïntegreerde aanpak, waarbij deze aspecten worden gecombineerd. Dit wordt tot op zekere hoogte veroorzaakt door de reikwijdte van de modellen, die zich vaak uitstrekt tot andere economische sectoren en zodoende het haalbare detailniveau beperkt. De belangrijkste belemmering voor het opnemen van gedragsaspecten in brandstofvervangingsmodellen wordt echter gevormd door het gebrek aan empirische gegevens. Er is dus sprake van een onderzoekslacune in de beschrijving van brandstofvervangingsbeslissingen in de industriële sector in energiesysteemmodellen; de integratie van economische-, technische- en gedragsaspecten in een gemeenschappelijk kader voor beleidsadvies.

Het proefschrift heeft dus tot doel het proces van brandstofvervanging zodanig te beschrijven dat het kan worden gebruikt als integraal onderdeel van een energiesysteemmodel dat wordt toegepast voor wetenschappelijk beleidsadvies. Om dit te bereiken worden de raakvlakken van economische belangen, gedrag en technische eisen onderzocht. Dit vereist het genereren van empirische gegevens over brandstofvervangingsbeslissingen. De belangrijkste onderzoeksvraag luidt dan ook:

"Hoe worden brandstofvervangingsbeslissingen in de energie-intensieve industrie genomen en hoe kunnen zij in een bottom-up-energiesysteemmodel voor het stimuleren van de keuze van energiedragers worden geïntegreerd?"



Afbeelding 8.1: Geabstraheerde proefschriftstructuur en informatiestroom tussen hoofdstukken

Vanwege de omvang en complexiteit van het onderwerp is deze onderzoeksvraag uitgesplitst in vijf deelvragen en onderzocht in vijf afzonderlijke delen zoals samengevat in afbeelding 8.1. Het eerste deel beschrijft de status quo van het energiegebruik in de industriële sector van de Europese Unie (hoofdstuk 2). Door de kennis over de toepassingen en temperatuurniveaus van de vraag naar warmte en koeling in de sector te vergroten, wordt de basis gelegd voor een modelontwikkeling die niet alleen recht doet aan economische overwegingen, maar ook aan technische aspecten van industriële processen.

In het tweede deel wordt het brandstofvervangingspotentieel in de energie-intensieve sectoren die in de EU-ETS zijn opgenomen, geraamd (hoofdstuk 3) op basis van een literatuurstudie. Deze richt zich op de beschikbare technologieën en brandstofvervangingsopties die in de nabije toekomst kunnen worden gerealiseerd en zo kunnen bijdragen aan de vermindering van de broeikasgasemissies tot 2030. Er wordt dus een technisch potentieel vanuit een bottom-up-perspectief beschreven, waarbij belangrijke industriële processen en actiegebieden worden geïdentificeerd.

Het derde deel (hoofdstuk 4) ondersteunt de operationalisering van brandstofvervangingsmodellen door de resultaten van een onderzoek onder besluitvormers in de Duitse industrie te presenteren. De verzamelde gegevens geven de voorkeuren aan voor stoomopwekkingstechnologieën, hetgeen, voor zover de auteur weet, nieuw is voor de industriële sector in de EU. Deze voorkeuren verbeteren het technisch-economisch onderzoek door middel van gedragsbeïnvloeding en verbeteren zo het vermogen van energiesysteemmodellen om werkelijke beslissingsresultaten weer te geven.

Het vierde deel beschrijft de ontwikkeling van een uitbreiding van de brandstofvervanging op het bestaande energiesysteemmodel FORECAST (hoofdstuk 5). Deze uitbreiding modelleert de brandstofvervanging als zijnde de beslissing tussen discrete alternatieven en maakt zo de concurrentie tussen technologieën en de bijbehorende energiedragers mogelijk. Daarnaast wordt in dit hoofdstuk het model geoperationaliseerd door het te baseren op gedragsparameters, die zijn afgeleid van een tijdreeksanalyse. Er wordt aangetoond dat het model in staat is om een groot deel van de waargenomen brandstofvervanging in het verleden te verklaren.

In het laatste deel (hoofdstuk 6) worden de voorgaande hoofdstukken samengevat in een scenarioanalyse van het praktische brandstofvervangingspotentieel in de Duitse industrie tot 2030. Er wordt onderzocht onder welke voorwaarden de overschakeling op een andere brandstof wordt bevorderd en hoe de Duitse sectorale doelstellingen voor de reductie van de uitstoot van broeikasgassen in de industrie kunnen worden ondersteund.

De respectievelijke deelonderzoeksvragen luiden als volgt:

1. Wat is het actuele gebruik van energie in industriële processen in de EU28 en wat is een zinvolle differentiatie van het energiegebruik voor de keuze van energiedragers? (hoofdstuk 2)

2. Welke brandstofvervangingsmaatregelen in belangrijke industriële processen in het EU-ETS worden in de literatuur besproken en hoe verhouden de bestaande mogelijkheden zich tot de uitstootreductiedoelstellingen? (hoofdstuk 3)

3. Hoe beïnvloeden de voorkeuren voor energiedragers in de industriële stoomopwekking de keuze van energiedragers en hoe kan een energiesysteemmodel deze opnemen? (hoofdstuk 4)

4. Hoe kan een bottom-up-energiesysteemmodel de brandstofkeuzes in energie-intensieve industrieën beschrijven en hoe kan een dergelijk model worden geparametriseerd? (hoofdstuk 5)

5. Welke economische stimulansen zijn nodig om de overschakeling op andere brandstoffen te ondersteunen om de klimaatdoelstellingen op middellange termijn te bereiken, rekening houdend met de economische-, technische- en gedragsmatige invloeden? (hoofdstuk 6)

8.2 Samenvatting van de resultaten

In dit deel worden de belangrijkste bevindingen van de afzonderlijke hoofdstukken samengevat en worden de belangrijkste conclusies ervan gepresenteerd.

Hoofdstuk 2 onderzoekt de status quo van het energiegebruik in de energie-intensieve industrieën van de lidstaten van de Europese Unie en Noorwegen, Zwitserland en IJsland (EU28+3). Het gaat uit van de officiële energiebalans van het bureau voor de statistiek van de Europese Unie en splitst deze gegevens op in eindgebruiksbalansen. Onder eindgebruik verstaan wij de toepassing van het energiegebruik (ruimteverwarming, procesverwarming, koeling) en het temperatuurniveau. Het past het energiesysteemmodel FORECAST toe om de energievraag op subsectoraal niveau te verdelen over de industriële processen. Deze bottom-up-benadering maakt het mogelijk om processpecifieke eigenschappen toe te wijzen aan de energievraag, bijvoorbeeld met betrekking tot de toegepaste technologieën, temperatuurniveaus en toepassingen. De modelresultaten geven een beknopt overzicht van de status quo van het energiegebruik en bieden zo nieuwe inzichten omtrent belangrijke gebieden voor actie. Het combineert dus de gegevens die het aanlevert tot een compleet beeld, dat verdere analyse mogelijk maakt. De resultaten van dit hoofdstuk genereren zo een basis voor verder werk aan de modellering van brandstofvervangingsmaatregelen.

De aanpak levert vergelijkbare resultaten op voor de afzonderlijke landen, omdat dezelfde methodologie op alle landen wordt toegepast. Tegelijkertijd komen de resultaten overeen met de officiële energiebalans. Het hoofdstuk bevat een onderzoek naar de geschiktheid van de energiebalansen en de geselecteerde nationale eindgebruiksbalansen. Het laat zien dat de bottom-up-benadering het beste werkt voor landen met een hoge totale energievraag en een brede industriële structuur, aangezien onzekerheden over individuele processen de resultaten in deze gevallen niet al te zeer beïnvloeden. Kleine landen kunnen een grote afwijking vertonen in de bottom-up-berekening, omdat hun industrie vaak bestaat uit een aantal kleinere en heterogene subsectoren. Grotere landen omvatten echter vaak een aantal welomschreven energie-intensieve processen, bijvoorbeeld de ijzer- en staalindustrie. De kleinste 20 landen zijn slechts goed voor ongeveer 15% van de verwarmingsvraag. Hoewel dit niet zo relevant is voor de EU28 als geheel, toont dit aan dat het onderzoek van de afzonderlijke landen aanvullende gegevens over hun industriële structuur vereist.

De belangrijkste bevindingen van het hoofdstuk omvatten de temperatuurverdeling voor verwarming en koeling in de EU28+3:

Warmte bij hoge temperaturen (meer dan 500°C) is goed voor 45% (1035 TWh) van de verwarmingsvraag in de EU28 (2315 TWh); drie subsectoren (ijzer en staal, basischemicaliën, niet-metaalhoudende mineralen) gebruiken 96% hiervan. Zij combineren de productie van producten met een hoge energie-intensiteit en een hoog productievolume, zoals ijzer en staal, ammoniak, ethyleen en cementklinker.

De vraag naar stoom in het bereik van 100°C tot 500°C (707 TWh) komt vooral voor in de papier- en voedingsindustrie, maar ook in een heterogene energiebalanscategorie "overige industrie", die niet verder werd onderzocht.

Het temperatuurbereik dat theoretisch toegankelijk is met lage-temperatuurtechnologieën (100°C - 200°C) zoals zonthermische systemen, warmtepompen en stadsverwarming bedraagt 760 TWh.

Onder deze temperatuur is ruimteverwarming goed voor 346 TWh. De ruimte- en proceskoeling gebruikt 100 TWh, waarvan de koeling tussen 0°C en 15°C bijna 50% uitmaakt (46 TWh).

Dit resultaat wordt versterkt door een analyse van belangrijke processen en hun temperatuurprofiel. De top vijf van processen op het gebied van de finale energievraag (hoogovens, papier, ethyleen, gewalst staal en klinkercalcinatie) zijn samen goed voor ongeveer 1000 TWh, bijna de helft van de verwarmingsvraag van de industrie.

Uit een landelijke evaluatie van de temperatuurprofielen blijkt dat grote landen (Duitsland, Italië, Frankrijk, Spanje, Nederland, Polen, met uitzondering van het Verenigd Koninkrijk) een vergelijkbaar aandeel van het warmtegebruik bij hoge temperaturen vertonen (tussen 40% en 50%). Deze landen zijn ook sterk afhankelijk van fossiele brandstoffen, waarbij ongeveer 70% van de vraag naar proceswarmte wordt gedekt door aardgas en kolen. Vooral hoge temperatuurwarmte wordt geleverd met fossiele brandstoffen. Dit is ook vergelijkbaar met het aandeel van de EU28 en geeft aan dat grote landen, bijvoorbeeld Duitsland, in het hoge temperatuurbereik als maatstaf kunnen dienen voor de EU28. Er bestaan grotere verschillen in het temperatuurbereik van 100°C - 200°C en onder 100°C. De industriële structuur van de afzonderlijke landen is zichtbaar in hun temperatuurverdeling (bijv. 100°C - 200°C proceswarmtegebruik in de papierindustrie van Finland en Zweden).

De onderzoeksvraag "*Wat is het huidige energiegebruik in industriële processen in de EU28 en wat is een zinvolle differentiatie voor de keuze van energiedragers*?" wordt daarom als volgt beantwoord: Het huidige energiegebruik van de industrie in de EU28 wordt gekenmerkt door een hoog aandeel van fossiele brandstoffen. Vooral proceswarmte bij hoge temperaturen maakt gebruik van een groot aandeel fossiele brandstoffen, maar ook van elektriciteit (bijvoorbeeld voor de productie van elektrisch staal). Biomassa wordt voornamelijk gebruikt in lage tot middelhoge temperatuurbereiken. Temperatuurniveaus vormen een geschikte wijze voor differentiatie van de vraag naar proceswarmte. Zij leveren een zinvolle differentiatie op met betrekking tot de toepasbare technologieën. Bovendien moet bij het onderzoek naar de overschakeling op andere brandstoffen rekening worden gehouden met individuele industriële processen.

De toegevoegde waarde van het werk in dit hoofdstuk is dat het - met een aanpak op procesniveau - een tot nu toe uniek detailniveau levert en in de industrie de basis vormt voor de evaluatie van de overschakeling op andere brandstoffen. Het legt dus de basis om zowel onderzoekers als beleidsmakers te ondersteunen bij het identificeren van mogelijkheden en actiegebieden voor energieefficiëntie en brandstofvervanging, bijvoorbeeld door het blootleggen van mogelijkheden voor technologieën met temperatuurbeperkingen zoals warmtepompen. De werkzaamheden zijn gericht op het nationale niveau. De toekomstige werkzaamheden evolueren naar een analyse op regionaal of zelfs installatieniveau, naarmate vragen over energiedistributie en infrastructuur aan belang winnen. In de volgende hoofdstukken wordt beschreven hoe het werk in dit proefschrift het energiesysteemmodel FORECAST uitbreidt met een brandstofvervangingsmodel. Het proefschrift stelt FORECAST in staat om consistente scenario's voor brandstofvervanging in de industrie te ontwikkelen; ook voor wat betreft prijsgevoeligheden, op basis van empirische gegevens. Het biedt dus de mogelijkheid om het effect van beleidsmaatregelen beter te onderzoeken dan voorgaande modellen.

Hoofdstuk 3 analyseert de opties voor brandstofvervanging in geselecteerde processen van de basismaterialenindustrieën en sectoroverschrijdende toepassingen. Er wordt een gemengde bottom-up/top-down-benadering toegepast om het totale brandstofvervangingspotentieel van de onder het EU-emissiehandelssysteem (EU-ETS) vallende industrieën in te schatten. Het EU-ETS omvat de energie-intensieve industrieën en dus de industrieën met het grootste effect op de emissies van het energieverbruik. Tegelijkertijd maakt het merendeel van de procesgerelateerde emissies deel uit van het EU-ETS. Het hoofdstuk richt zich op de belangrijkste sectoren, aan de hand van hun totale emissies: raffinaderijen, ijzer en staal, niet-metaalhoudende mineralen (cement, kalk, glas en keramiek), papier en basischemicaliën. Samen zijn deze sectoren goed voor 95% (547 MtCO2-eq.) van de EU-ETS-uitstoot, 64% van de (directe) industriële emissies van de EU28 in het kader van het EU-ETS [12] en 75% van de eindvraag naar energie van de industrie binnen de EU28 [1].

Het energiegebruik van de onderzochte processen wordt tot op heden gedomineerd door fossiele brandstoffen. Aardgas en steenkool (inclusief cokes) zijn goed voor 46% van de eindvraag naar energie. De overige 54% bestaat uit elektriciteit (27%), olie (9%), duurzame energie (7%) en overige (11%). Met de focus op de reductie van de uitstoot in de industriesector analyseert het hoofdstuk de mogelijkheden om over te schakelen op biomassa en elektriciteit. Wij beschouwen de overschakeling van steenkool naar natuurlijke biomassa niet als duurzaam, omdat dit alleen maar zou afleiden van een emissiereductie tot vrijwel nul, hetgeen noodzakelijk is binnen een 2050-perspectief[103]. Dit wordt gemotiveerd door onze kennis van klimaatverandering en het inzicht dat het gebruik van fossiele brandstoffen in de eerste helft van deze eeuw moet worden geëlimineerd om de omvang van de opwarming van de aarde te verminderen. Bovendien moet de vermindering van de uitstoot van broeikasgassen (BKG) reeds tot 2030 sterk worden verminderd om onder de 2°C te blijven en, indien mogelijk, de stijging van de mondiale temperatuur tot 1,5°C te beperken. Daarom richt het hoofdstuk zich op technologieën die onmiddellijk beschikbaar zijn of tot 2030 een relevante impact kunnen hebben. Dit vereist dat de analyse wordt beperkt tot technologieën met een technologische gereedheid

[103] Dit type brandstofschakelaar is mogelijk binnen het model dat in dit proefschrift is ontwikkeld, maar werd niet specifiek onderzocht.

(TRL[104]) van 6 of hoger. Dit betekent dat de technologieën op zijn minst gevalideerd zijn in relevante omgevingen en geschikt zijn voor demonstratie-installaties. Dit vereist nog steeds een ambitieuze ontwikkeling om tegen 2030 marktrijp te kunnen zijn.

De resultaten tonen aan dat er in verschillende industrieën een aanzienlijk potentieel bestaat voor de overschakeling op biomassa en elektriciteit. Tot de meest invloedrijke maatregelen behoren het gebruik van biogene brandstoffen bij de productie van kalk en klinkers (57 MtCO2-eq.), het gebruik van biomassa in hoogovens en de overschakeling op elektrische vlamboogovens (EAF[105]) met 35 MtCO2-eq., de vervanging van ingekochte brandstoffen in raffinaderijen (42 MtCO2-eq.) en het gebruik van biomassa of elektriciteit in andere stoomsystemen en -ovens (28 MtCO2-eq.). De combinatie van deze en andere opties vertegenwoordigt een reductiepotentieel van 184 MtCO2-eq. in 2030 (afbeelding 8.2). Dit vormt ten opzichte van 2016 een reductie van 34% en brengt het emissiereductietraject in overeenstemming met 1,5°C-scenario's die een reductie van 55% ten opzichte van 1990 vereisen. De emissies van ongeveer 275 MtCO2-eq. blijven echter onaangetast door de besproken opties voor brandstofschakelaars.

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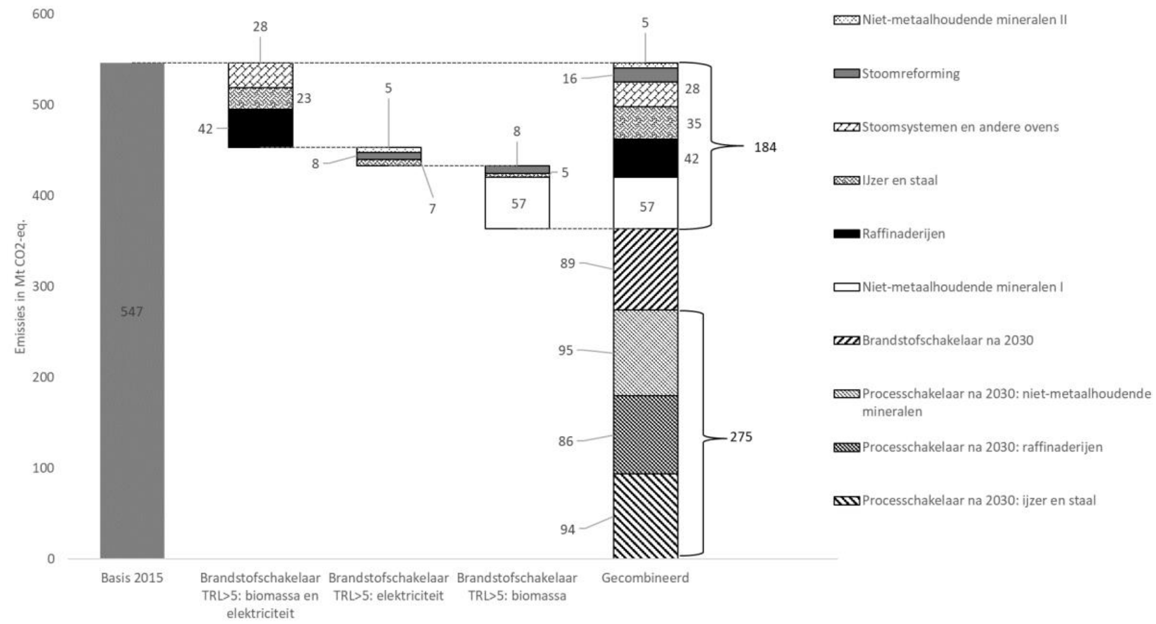
104 TRL-definitie volgens Horizon 2020 [13]:
TRL 1 - basisbeginselen in acht genomen
TRL 2 - technologieconcept geformuleerd
TRL 3 - experimenteel bewijs van het concept
TRL 4 - technologie gevalideerd in laboratorium
TRL 5 - technologie gevalideerd in relevante omgeving
TRL 6 - technologie gedemonstreerd in relevante omgeving
TRL 7 - demonstratie van een systeemprototype in een operationele omgeving
TRL 8 - systeem compleet en gekwalificeerd
TRL 9 - daadwerkelijk bewezen systeem in een operationele omgeving

105 De verschuiving naar EAF op basis van schroot vormt zowel een circulaire besparingsactie (omdat gerecycled staal als grondstof wordt gebruikt) als een brandstofschakelaar. Bovendien sluit zij aan bij mogelijke lange-termijntrajecten in de richting van de productie van staal op basis van waterstof.



Afbeelding 8.2: Emissiereductiepotentieel door brandstofvervangingsmaatregelen, besproken in hoofdstuk 4 en resterende emissies;

Beide gerichte mitigatiemogelijkheden, hernieuwbare elektriciteitsproductie en duurzame biomassa, zijn beperkt. Schattingen van het beschikbare duurzame potentieel van biomassa en hernieuwbare elektriciteit in de Europese Unie tonen aan dat er op lange termijn (2050) mogelijkheden bestaan voor het leveren van de beschreven brandstofschakelaar. De beschikbaarheid van deze energiedragers in 2030, in de vereiste hoeveelheden is echter twijfelachtig, daar de ontwikkeling ervan afhankelijk is van het politieke engagement. Met een veronderstelde realisatie van 50% van het 2050-potentieel tot 2030 zou het beschikbare aanbod van duurzame biomassa en hernieuwbare energiebronnen niet volstaan om de aanvullende vraag te dekken, die door de onderzochte opties voor de brandstofschakelaar wordt gegenereerd. De belangrijkste conclusie van dit hoofdstuk is dus dat de overschakeling op een andere brandstof wel degelijk een belangrijke rol speelt bij het tegengaan van de klimaatverandering: de industriesector beschikt over technische mogelijkheden voor het overschakelen op een minder broeikasgasintensief warmteaanbod. De belangrijkste voorwaarde voor het realiseren van deze opties wordt echter gevormd door de concurrerende beschikbaarheid van elektriciteit en biomassa. Wat dit betekent en hoe het concurrentievermogen van fossiele brandstoffen kan worden gecreëerd, vormt het onderwerp van de volgende hoofdstukken.

De onderzoeksvraag "*Welke brandstofvervangingsmaatregelen in belangrijke industriële processen in het EU ETS worden in de literatuur besproken en hoe verhouden de bestaande mogelijkheden zich tot de emissiereductiedoelstellingen*?" wordt daarom als volgt beantwoord: In alle subsectoren van de basismaterialenindustrie bestaan grote brandstofvervangingsopties. Vooral het gebruik van biomassa en elektriciteit ter vervanging van fossiele brandstoffen in ijzer en staal, chemicaliën en niet-metaalhoudende mineralen vertoont een groot potentieel. Al deze mogelijkheden samen zouden kunnen volstaan om de uitstoot van broeikasgassen te verminderen volgens 1,5°C-scenario's voor de opwarming van de aarde. Toch vormt het overschakelen op een andere brandstof slechts één maatregel en moeten er aanvullende opties worden onderzocht, zoals energie- en materiaalefficiëntie, circulaire economie en innovatieve processen, om er maar een paar te noemen. Deze hebben interacties en terugkoppelingen en zullen van invloed zijn op de kenmerken van de technologie en het energiegebruik.

In dit hoofdstuk wordt alleen het technische potentieel onderzocht. Uit het literatuuronderzoek blijkt echter ook duidelijk dat economische barrières de belangrijkste reden vormen voor het niet realiseren van belangrijk potentieel. Het belangrijkste is dat de hoge elektriciteitsprijzen in vergelijking met bijvoorbeeld aardgas de aantrekkelijkheid van proceswarmte-elektrificatie sterk beperken. Het geïdentificeerde potentieel houdt ook geen rekening met de investeringscycli in de industrie[106]. Gezien het beperkte tijdsbestek (2030) legt de natuurlijke voorraadomzet strikte beperkingen op aan de haalbare brandstofschakelaar. Deze twee kernpunten zijn echter bepalend voor de vraag of een brandstofvervanging daadwerkelijk plaatsvindt of een potentieel blijft. In de volgende hoofdstukken komen deze vragen aan de orde.

De toegevoegde waarde van dit hoofdstuk ligt in het verzamelen, interpreteren en kwantificeren van brandstofvervangingspotentieel, dat in de sector- of processpecifieke literatuur kan worden gevonden. Dit hoofdstuk geeft een uitgebreid overzicht van de momenteel besproken brandstofvervangingsmaatregelen in energie-intensieve processen die onder het EU-ETS vallen en geeft een schatting van het gecombineerde technische potentieel. Het levert zodoende de basis voor de economische evaluatie van dit potentieel en de integratie in energiesysteemmodellen, die in de volgende hoofdstukken worden gepresenteerd.

In hoofdstuk 4 wordt de basis gelegd voor het opnemen van gedragsaspecten in een brandstofvervangingsmodel. Via een enquête worden “aangegeven” voorkeuren voor stoomopwekkingstechnologieën afgeleid. Wij richten ons op stoomopwekking als een groot, relatief homogeen eindgebruik in de industrie. Aangegeven voorkeuren, die reacties vormen op theoretische situaties, hebben het voordeel dat zij “wat als”-aspecten op kunnen nemen, daar de deelnemer aan de enquête wordt geconfronteerd met theoretische alternatieven die nog niet noodzakelijkerwijs bestaan of nog niet relevant zijn in de markt[107]. Hun nadeel ligt in het mogelijke gebrek aan betrokkenheid, omdat de keuze geen echte gevolgen heeft.

In dit specifieke geval hebben wij besluitvormers in Duitse bedrijven, die stoomgeneratoren exploiteren, gevraagd naar de gepercipieerde aantrekkelijkheid van de verschillende mogelijkheden voor stoomopwekking. De deelnemers werkten in de subsectoren “voedselverwerking”, “chemische- en farmaceutische productie” en “papier- en kartonproductie”. De steekproefdistributie was

106 In het geval van stoomsystemen wordt uitgegaan van een voorraadrotatie van 50% tot 2030.

107 Deze moeten echter dicht bij de werkelijkheid liggen of op zijn minst aannemelijk zijn om zinvolle resultaten te kunnen verkrijgen.

representatief voor de bedrijfsdistributie van de onderzochte subsectoren. De deelnemers werden geconfronteerd met drie sets stoomgeneratoren, die elk drie systemen omvatten. Binnen deze selectie moesten de deelnemers de aantrekkelijkheid van de systemen bepalen. Deze aantrekkelijkheid kan worden vertaald naar monetaire waarden door kruisverwijzingen naar de kosten van stoomopwekking te gebruiken.

De evaluatie van de antwoorden leverde significante resultaten op voor alle onderzochte attributen (kosten van stoomopwekking, energiedrager, technische beschikbaarheid). Dit betekent dat zij waarschijnlijk allen relevant zijn voor de keuze van het systeem. Met name het energiedragerattribuut speelde een belangrijke rol in de besluitvorming[108]. Kolen en olie zijn aanzienlijk minder aantrekkelijk dan aardgas en biomassa.

De belangrijkste conclusies zijn dat er voorkeuren voor energiedragers bestaan en dat deze van belang zijn. Zij vormen dus een noodzakelijk onderdeel van de overwegingen met betrekking tot de overschakeling op een andere brandstof. De onderzoeksvraag "Hoe beïnvloeden energiedragervoorkeuren bij industriële stoomopwekking de keuze van energiedragers en hoe kunnen zij in een energiesysteemmodel worden opgenomen?" kan daarom op de volgende wijze worden beantwoord: energiedragervoorkeuren hebben een significante invloed op de keuze van stoomopwekkingstechnologieën en strekken zich verder uit dan alleen prijsverschillen. Hun effect op de keuze van de technologie en de energiedrager kan in geld worden uitgedrukt. Dit maakt het mogelijk om ze op te nemen in gemeenschappelijke techno-economische evaluaties.

De toegevoegde waarde van dit hoofdstuk wordt gevormd door de kwantificering van de voorkeuren voor het vervangen van brandstof in stoomsystemen. Zij leveren een referentiepunt voor toekomstig onderzoek en toepassing in energiesysteemmodellen. De relatie tot de opwekkingskosten maakt integratie mogelijk in bottom-up-energiemodellen die de kosten berekenen, bijvoorbeeld op basis van kapitaal- en exploitatie-uitgaven. De resultaten kunnen zo worden geoperationaliseerd om de prijsresponsiviteit van de modellen te verhogen. Vanuit een maatschappelijk perspectief kan de toegenomen kennis over systeemvoorkeuren ondersteuning bieden voor een gericht beleidsontwerp, om de overstap naar koolstofarme technologieën te stimuleren.

Hoofdstuk 5 ontwikkelt een modeluitbreiding op het bestaande bottom-up-energievraagsimulatiemodel FORECAST. Deze uitbreiding richt zich op brandstofvervanging in hoge temperatuurprocessen en integreert technische-, economische- en gedragsmatige aspecten, voortbouwend op de technische mogelijkheden die in hoofdstuk 3 worden geïdentificeerd. Het is dus de bedoeling om een uitgebreid overzicht te geven van haalbare brandstofvervangingen onder

108 Een kostenverhoging van 1 €ct/kWh vermindert de aantrekkelijkheid van een systeem met 0,410 punten en één procent van de uitvaltijd met 0,383 punten. De verandering van de energiedrager naar aardgas of biomassa uit steenkool verhoogt de aantrekkelijkheid met 1,802 punten, van olie met 0,926 punten. In geld uitgedrukt komt dit neer op een kostenstijging van 2,26 €ct/kWh voor olie en 4,40 €ct/kWh voor steenkool. Gelet op de mogelijke kosten van 4 - 10 €ct/kWh is dit een sterk effect.

uiteenlopende randvoorwaarden. Bijzondere aandacht wordt besteed aan prijsgevoeligheid, voorkeuren van marktdeelnemers en technische beperkingen die de energiedragers van bepaalde toepassingen uitsluiten. Bij deze overwegingen wordt gebruik gemaakt van de in hoofdstuk 2 afgeleide temperatuurprofielen, waarbij de nadruk ligt op processen met hoge temperaturen, omdat deze in de EU28 van groot belang zijn. Dit hoofdstuk genereert middels een tijdreeksanalyse bovendien "geopenbaarde" voorkeuren voor industriële ovens. Het versterkt dus de empirische basis voor de modellering van brandstofschakelaars, als aanvulling op de gegevens die in hoofdstuk 4 voor de stoomopwekking zijn verzameld.

Het model benadert brandstofvervangingsbeslissingen vanuit het perspectief van een geïdealiseerde besluitvormer binnen de specifieke omgeving. De idealisering bestaat uit de aanname dat de besluitvormer een vertegenwoordiger van de groep is. Een groep wordt gedefinieerd door industriële subsectoren (en landen)[109]. De besluitvormer is dus geen echte persoon of instelling, maar een vertegenwoordiger die dezelfde beslissingen neemt als het geheel van alle marktpartijen. Dit resulteert in een verdeling van de marktaandelen van de beschikbare technologieën. Het besluitvormingsproces is gebaseerd op de theorie van de discrete keuze, waarbij discrete opties als alternatieven worden gepresenteerd. De concurrentie tussen deze alternatieven wordt gevormd door de prijsgevoeligheid.

Hoewel economische invloeden een grote invloed hebben op de keuze van de energiedrager, bepalen aanvullende parameters de uitkomst van het model. De nieuwigheid van het werk bestaat uit de identificatie van voorkeuren voor energiedragers[110], energie-intensieve subsectoren en landen die in de energiebalansen van Eurostat zijn opgenomen. Deze voorkeuren wijzigen de economische evaluatie van de energiedragers om de aantrekkelijkheid of, voor wat het model betreft, het nut te definiëren. Deze aantrekkelijkheid komt voort uit de constatering dat de prijzen alleen het gebruik van energiedragers niet kunnen verklaren. De voorkeuren worden afgeleid uit de analyse van tijdreeksen. Bij deze benadering wordt het ontwikkelde brandstofvervangingsmodel achterwaarts toegepast op een waargenomen periode waarvoor zowel het resultaat (energiedrageraandeel) als de input (prijzen) bekend zijn. Het maakt gebruik van een "kleinste-kwadraten-aanpak" ten opzichte van de geobserveerde ontwikkelingen in deze periode. De resulterende parameters bepalen het besluitvormingsproces en vooral de prijsgevoeligheid van de besluitvormer. Het brandstofvervangingsmodel is dus in staat om de reactie van de subsectoren op prijsveranderingen weer te geven. Andere invloeden op de keuze van de energiedrager, bijvoorbeeld bestaande infrastructuur en procestechnologieën ter plaatse of langlopende leveringscontracten, worden

109 Zo kiest de ijzer- en staalindustrie in Duitsland voor andere energiedragers dan die in Italië. De verschillende aandelen van de primaire en secundaire productieroute kunnen dit deels verklaren. De niet-metaalhoudende mineralen gebruiken andere energiedragers dan de papierindustrie, vanwege processpecifieke eigenschappen (mogelijkheid om afval te gebruiken bij klinkerverbranding, biomassa-residuen bij pulpproductie).

110 Om methodologische redenen werden sommige energiedragers gegroepeerd, zo werden verschillende vaste brandstoffen gegroepeerd als "kolen" (zie hoofdstuk 2).

geabstraheerd in modelparameters die de reactie op prijssignalen bepalen. Deze modelparameters geven de voorkeuren van de subsectoren weer.

“Geopenbaarde” voorkeuren weerspiegelen de waargenomen aantrekkelijkheid in de betreffende periode. Zij zijn dus zeer geschikt voor het simuleren van business-as-usual-ontwikkelingen, maar het ontbreekt aan informatie over reacties op drastische veranderingen, bijvoorbeeld prijsschokken of sterk beleidsgestuurde invloeden. Daar het niet duidelijk is hoe deze voorkeuren in de loop van de tijd veranderen, is de beste beschikbare aanname dat zij constant blijven. Hierdoor zou flexibiliteit kunnen worden onderschat. Hoewel de eenvoudige beschikbaarheid van deze voorkeuren al een verbetering vormt, moet de kennis over de reactie van de industrie op verstorende- en gedragsveranderingen dus verder worden verdiept.

De onderzoeksvraag "*Hoe kan een bottom-up-energiesysteemmodel brandstofkeuzes in energie-intensieve industrieën beschrijven en hoe kan dit worden geparametriseerd*?" wordt op deze wijze beantwoord: de implementatie van een discreet keuzemodel voor brandstofvervanging in een bottom-up-energiesysteemmodel vereist definitie van geschikte aggregaten voor zowel energiedragers als besluitvormers. De discrete keuzebenadering creëert een concurrentie tussen energiedragers en de aantrekkelijkheid binnen deze concurrentieituatie wordt beïnvloed door prijssignalen, technische aspecten en groepsspecifieke voorkeuren. De parameters van het model kunnen worden afgeleid uit tijdreeksanalyse (“aangegeven voorkeuren”), met behulp van een toereikende determinatiecoëfficiënt (gemiddelde van 0,64). Kleine landen hebben speciale aandacht nodig omdat statistische fouten de resultaten sterker beïnvloeden. Over het algemeen is een geavanceerde bottom-up-processtructuur vereist om de brandstofkeuze in de industrie weer te kunnen geven.

De toegevoegde waarde van dit hoofdstuk bestaat uit het genereren van gekwantificeerde voorkeuren voor de keuze van energiedragers in hoge-temperatuurprocessen. Deze voorkeuren worden toegepast in een discrete-keuze-brandstofvervangingsmodel, als uitbreiding op een bottom-up-energiesysteemmodel. In deze combinatie creëren zij een prijsgevoeligheid van brandstofvervanging en maken zij de evaluatie van economische- en politieke invloeden op het gebruik van energiedragers mogelijk. Het ontwikkelde model omvat technische aspecten op procesniveau en gedrags- en economische aspecten op subsectorniveau. Het is het eerste model dat deze drie aspecten in een geïntegreerde aanpak benadert. Het ondersteunt dus beleidsadvies en onderzoek op het gebied van brandstofvervanging middels een betere representatie van de werkelijkheid dan voorheen het geval was.

In hoofdstuk 6 wordt de rol van prijssignalen bij de vervanging van brandstoffen over het algemeen en naar biomassa en elektriciteit in het bijzonder onderzocht. Het combineert de resultaten van de vorige hoofdstukken tot uitgebreide brandstofvervangingsscenario's. Het omvat dus hoge temperatuur-proceswarmte in ovens (zie hoofdstuk 5), stoomopwekking (zie hoofdstuk 4) en warmwater- en ruimteverwarming[111], waarbij de structuur van de warmtevraag die in hoofdstuk 2 wordt opgewekt, wordt geïmplementeerd. Het presenteert de in hoofdstuk 3 geïdentificeerde brandstofvervangingsopties, waaronder het gebruik van biomassa in hoogovens en cementproductie, en het elektrificatiepotentieel in de stoomopwekking. Het in hoofdstuk 5 ontwikkelde en geparametriseerde model wordt toegepast op de vraag naar hoge temperatuur-proceswarmte. De brandstofvervangingsbeslissingen in de stoomopwekking worden beïnvloed door de voorkeuren die in hoofdstuk 5 worden geïdentificeerd.

De scenarioanalyse omvat vier scenario's, waarin verschillende beleidsinstrumenten worden onderzocht (tabel 8.1). Ten eerste een basisscenario zonder subsidies, CO2-prijs, snellere technologiebeurs- of regulerende maatregelen[112]. Ten tweede een investeringsscenario zonder subsidies op de productie van proceswarmte, maar wel op de investering hierin (CAPEX-gecentreerd). Ten derde, een vervangingsscenario met een hogere stoom- en ovenuitwisseling, hetgeen leidt tot een snellere transitie. Ten vierde, een reguleringsscenario, waarbij naast het vervangingsscenario nieuwe stoominstallaties op basis van fossiele brandstoffen worden verboden en de technologie-uitwisseling nog verder wordt opgevoerd.

Tabel 8.1: Scenariostructuur hoofdstuk 6

	Scenario	**Basis**	**Investering**	**Vervangering**	**Regulering**
Kader	Productieactiviteit	Afhankelijk van product: langzame of stagnerende groei			
	Prijzen energiedrager	Volgt historische trends			
Maatregelen	CO2-prijs	25EUR/tco2 in 2020, lineaire groei tot 50 EUR/tco2 in 2030			
	Subsidies	Ja	Nee	Ja	Ja
	Investeringsondersteuning	Nee	100%	Nee	Nee
	Vroegtijdige vervanging	Nee	Nee	75% van technische levensduur 2025-2030	75% van technische levensduur 2025-2030
	Verbod op fossiele brandstoffen nieuwe installaties	Nee	Nee	Nee	Na 2025
	Rationele keuze	50%	50%	75%	75%-100%

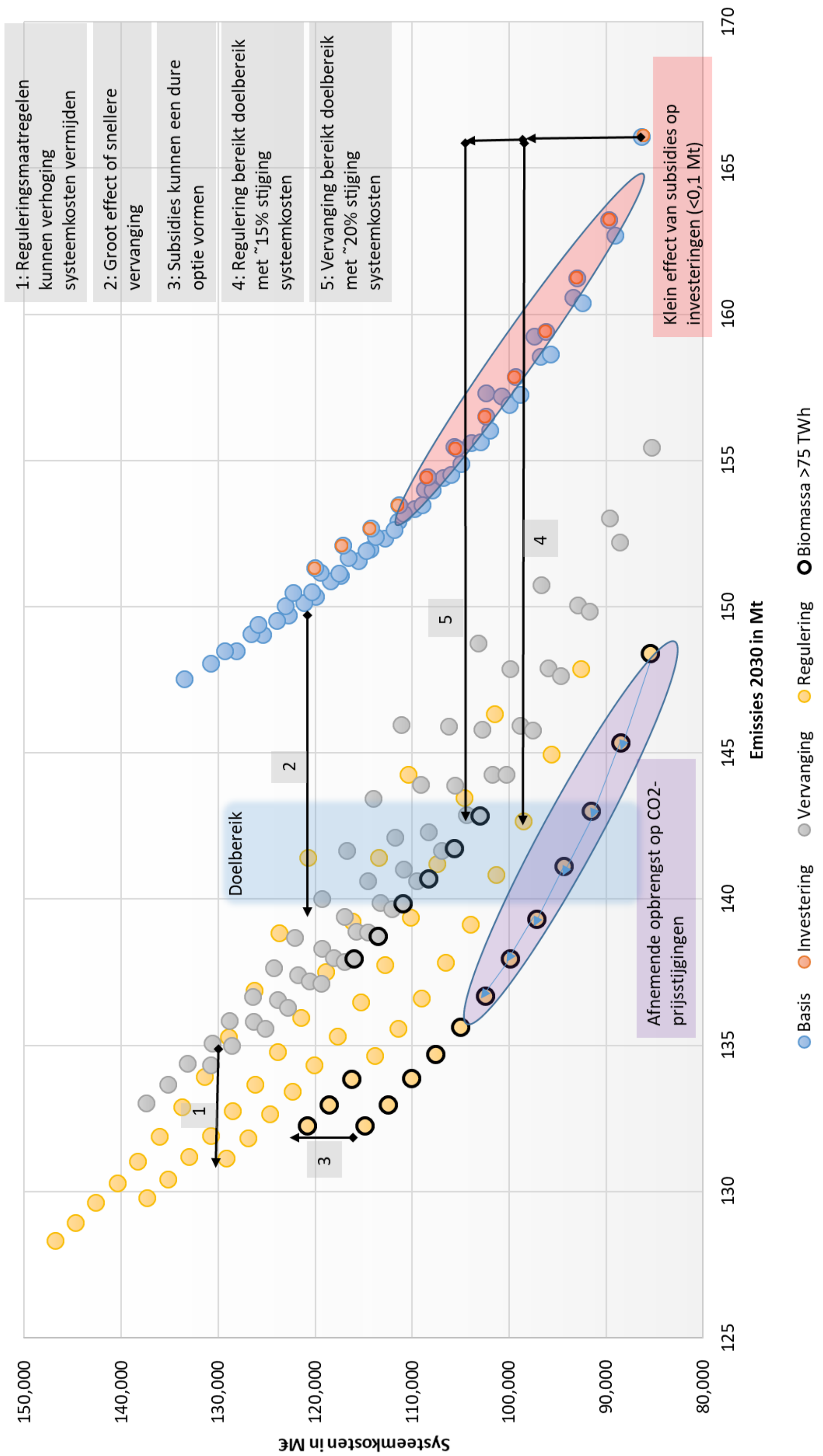
Alle beleidsmaatregelen zijn bedoeld om de aantrekkelijkheid van BKG-arme technologieën te vergroten, of die van BKG-intensieve technologieën te verminderen. Zij ondersteunen dus de overgang naar minder broeikasgasemissies. In dit geval kiezen wij de Duitse doelstelling voor 2030 voor de industriesector als eindpunt van het model. In het hoofdstuk wordt dus onderzocht hoe brandstofvervangingsmaatregelen kunnen bijdragen aan het bereiken van deze doelstelling en welk beleid deze kan ondersteunen.

De kracht van het beleid (CO2-prijs en OPEX-subsidies) wordt gevarieerd in een reeks modellen en het effect ervan op de uitstoot van broeikasgassen wordt gemeten. De resultaten tonen aan dat zonder

111 Gebaseerd op het werk van Biere [14].

112 In latere variaties worden subsidies voor het gebruik van elektriciteit voor de productie van proceswarmte (OPEX-centrisch) en een prijs voor de CO2-uitstoot toegevoegd.

verhoogde technologie-uitwisseling zelfs hoge subsidies (vrijwel gratis elektriciteit voor proceswarmte) en CO2-prijzen (300 €/tCO2-eq.) niet volstaan om de Duitse doelstellingen voor 2030 voor de industriesector op eigen kracht te halen. Zij tonen bovendien aan dat investeringssubsidies niet geschikt zijn voor het verhogen van de overgangssnelheid, omdat de kapitaaluitgaven vrijwel verwaarloosbaar zijn in vergelijking met de bedrijfskosten, in het bijzonder de energiekosten. Om de doelcorridor van 140 MtCO2-eq. tot 143 MtCO2-eq. BKG-emissies in de industriesector in 2030 te bereiken, dient de technologie-uitwisseling te worden opgevoerd. Een verbod op fossiele brandstoffen kan de vereiste economische stimulansen verminderen. Ten slotte komt zelfs een ambitieus beleid ter ondersteuning van de overschakeling op andere brandstoffen niet in aanmerking voor een traject dat verenigbaar is met een raming van 1,5°C voor een vermindering van de uitstoot die verenigbaar is met de opwarming van de aarde (afbeelding 8.3)



Afbeelding 8.3: Systeemkosten boven BKG-emissies voor variaties in elektriciteitssubsidies en CO2-prijzen

Een van de redenen voor het beperkte effect van de overschakeling op een andere brandstof wordt gevormd door de emissies die door deze maatregel niet kunnen worden beïnvloed: cokesgebruik in hoogovens, bijproducten in raffinaderijen en procesgerelateerde emissies, bijvoorbeeld in de cementproductie. Deze emissies zijn goed voor bijna de helft van de totale uitstoot van de industrie in het kader van het EU-ETS en een vergelijkbaar aandeel van de industriële emissies in Duitsland. Doordat dit aandeel van de emissies weinig tot geen prijsgevoeligheid vertoont, is de prijsgevoeligheid van de totale emissies beperkt en zijn sterke stimulansen en voorschriften vereist voor het terugdringen van emissies. Aanvullende maatregelen, zoals een vermindering van de vraag en een grotere materiaalefficiëntie, lijken dus al tot 2030 noodzakelijk.

In de analyse wordt gekozen voor een technische benadering, waarbij economische stimulansen en technologische wisselkoersen van elkaar worden gescheiden. Het is aannemelijk dat hoge subsidies en CO2-prijzen leiden tot een versnelde vervanging van oude installaties. Zelfs investeringssubsidies zouden in dit verband nuttig kunnen zijn, indien zij worden ondersteund door beleid dat de exploitatiekosten beïnvloedt. De onderzoeksvraag "Welke economische stimulansen zijn nodig om de overschakeling op andere brandstoffen te ondersteunen teneinde de klimaatdoelstellingen op middellange termijn te bereiken, rekening houdend met economische-, technische- en gedragsbeïnvloeding?" wordt op deze wijze beantwoord: om de overschakeling op andere brandstoffen in overeenstemming met de klimaatdoelstellingen voor de middellange termijn te ondersteunen (exemplarisch voor de Duitse industriedoelstelling voor 2030), moeten twee aspecten in aanmerking worden genomen: ten eerste dient er een business case voor broeikasgasarme technologieën te bestaan. De kosten voor de productie van proceswarmte moeten lager zijn dan de kosten van alternatieven die met fossiele brandstoffen worden gestookt, hetgeen met de huidige en te verwachten prijzen van energiedragers alleen mogelijk lijkt met overheidsinterventie (bijvoorbeeld CO2-prijsstelling en subsidies voor CO2-arme energiedragers). De vrijstelling van de door de overheid opgelegde componenten van de elektriciteitsprijs, die in Duitsland al voor bepaalde industrieën geldt, verlaagt de elektriciteitsprijs met 11 €ct/kWh. Dit valt ruim binnen de marge waarin relevante reacties in hoofdstuk 6 konden worden geobserveerd, indien dit op alle industrieën zou worden toegepast. Ten tweede, zelfs wanneer er aantrekkelijke technologieën met een laag broeikasgasgehalte op de markt zijn, is de snelheid van de voorraadrotatie die in de afgelopen decennia is waargenomen niet voldoende om fossiele brandstoffen snel genoeg af te bouwen. De resterende tien jaar tot 2030 vragen dus om onmiddellijke actie en meer inspanningen. Het is noodzakelijk om proceswarmte-installaties te vervangen voordat hun technische levensduur verstrijkt. Bijgevolg betekent elke installatie voor fossiele brandstoffen vanaf nu een stap in de verkeerde richting en waarschijnlijk een investering die zal stranden. Bovendien blijkt uit de grote hoeveelheid emissies die niet door de overschakeling op een andere brandstof worden aangepakt, dat er maatregelen moeten worden genomen om nieuwe productieprocessen in te voeren en de emissiebronnen die tot nu toe vrij moeilijk te verminderen zijn, te vervangen: hoogovens, raffinaderijen, procesgerelateerde emissies.

De toegevoegde waarde van dit hoofdstuk bestaat uit de kwantificering van twee veelbesproken BKG-emissiereductiemaatregelen (elektrificatie en CO2-prijsstelling) in een geïntegreerde modelaanpak. De toegepaste scenarioanalyse brengt belangrijke hefbomen voor het vergemakkelijken van de overschakeling op andere brandstoffen (beurs- en bedrijfskosten) aan het licht. De reacties op prijssignalen ondersteunen de beleidsontwikkeling (bijvoorbeeld de definitie van niet-ETS-koolstofprijzen in Duitsland). De methodologie van de scenarioanalyse maakt het mogelijk, onzekerheden in de kadergegevens weg te nemen (bijv. energiedragerprijzen en economische groei). Het hoofdstuk draagt dus met empirisch onderbouwde inzichten bij aan lopende en zeer relevante maatschappelijke discussies.

8.3 Conclusies

De belangrijkste conclusie van dit proefschrift is dat het overstappen op andere brandstoffen een belangrijke maatregel vormt voor het aanvaarden van een van de grootste uitdagingen van deze eeuw, namelijk het tegengaan van de antropogene klimaatverandering. Deze biedt mogelijkheden die in het komende decennium kunnen worden benut (hoofdstuk 3 en 6). Vanuit technisch oogpunt zijn maatregelen aan de vraagzijde, zoals een groter gebruik van biomassa, in veel van de huidige processen haalbaar. Evenzo is elektrificatie van de vraag naar proceswarmte zowel in het hoge- als in het middentemperatuurbereik mogelijk. Voorbeelden met een grote impact zijn de geleidelijke injectie van biomassa in roterende- (cement), schacht- (kalk) en hoogovens (ijzer) en de opwekking van stoom op basis van elektriciteit. Toch blijven grote emissiebronnen onaangetast door het overschakelen op andere brandstoffen en moeten zij anders worden benaderd (hoofdstuk 3). Voor stoomopwekking bestaat de voorkeur voor minder emissie-intensieve technologieën en deze kunnen de overstap van fossiele brandstoffen ondersteunen, indien economische omstandigheden dit toelaten (hoofdstuk 4). Voor industriële toepassingen met hoge temperaturen, die 45% van de vraag naar industriële verwarming in de EU28 vertegenwoordigen (hoofdstuk 2), bleek uit het proefschrift dat er een aanzienlijke prijsgevoeligheid bestaat, hetgeen erop wijst dat economische stimulansen voor de overschakeling op een andere brandstof doeltreffend kunnen zijn (hoofdstuk 5). Deze stimulansen moeten zeer hoog zijn, maar ondersteunende maatregelen zoals een snellere beurs zorgen voor een aanzienlijke vermindering van de vereiste economische druk en/of subsidies (hoofdstuk 6).

Hoewel de besproken brandstofovergangsopties technisch beschikbaar zijn, worden zij economisch gezien als een uitdaging ervaren. Elektriciteit is niet concurrerend in industriële stoomopwekking en beperkt zich tot speciale toepassingen in het hoge temperatuurbereik. Over het algemeen is aardgas de aantrekkelijkere energiedrager. In het huidige economische klimaat zou een sterke beleidsinvloed nodig zijn om een omschakeling naar direct gebruik van elektriciteit voor procesverwarming te stimuleren. De belangrijkste motivatie van het ontwikkelde model wordt gevormd door het doel om haalbare en aannemelijke transformatiepaden naar een duurzame industriële energievraag te bepalen. Uit hoofdstuk 4 en 6 is gebleken dat er aanzienlijke mogelijkheden bestaan om op een andere brandstof over te schakelen, hetgeen bijdraagt aan dit doel. Deze zijn in vergelijking met fossiele brandstoffen echter vaak niet concurrerend vanwege de hoge energiedragerprijzen. Het aanbod van concurrerende brandstoffen met een lage uitstoot en duurzame elektriciteit vormt dan ook een van de belangrijkste voorwaarden voor de overschakeling op een andere brandstof. Uit hoofdstuk 6 blijkt dat subsidies op de elektriciteitsprijs van 5 €ct/kWh in het voorbeeld van Duitsland zouden volstaan om voldoende elektriciteit te stimuleren (toename van ~15 TWh voor procesverwarming ten opzichte van het basisscenario), om tot een oplossing te komen die verenigbaar is met de industriële 2030-doelstellingen (vermindering van de broeikasgasemissies met 50% ten opzichte van 1990). Een substantieel elektriciteitsverbruik (ruwweg een verdubbeling van het huidige elektriciteitsverbruik voor procesverwarming tot 130 TWh) vereist echter hogere subsidies (tot 20 €ct/kWh), waardoor er effectief elektriciteit wordt geleverd tegen of onder de aardgasprijzen.

Uit hoofdstuk 6 blijkt dat de technologiekoers van de beurs een belangrijke factor vormt voor het bereiken van de klimaatdoelstellingen voor de middellange termijn. De effectenbeurs wordt vaak belemmerd door lange looptijden en herinvesteringscycli in de industrie. Synthetische brandstoffen daarentegen zouden fossiele brandstoffen kunnen vervangen zonder dat er technische veranderingen aan de vraagzijde nodig zijn. Zij zouden dus een langdurige beurs kunnen omzeilen, vooral voor wat industriële ovens betreft. Het is echter nog onduidelijk hoe deze brandstoffen in voldoende hoeveelheden en tegen concurrerende prijzen kunnen worden geproduceerd. Bijkomende onzekerheden worden gevormd door onder meer de duurzaamheid van dergelijke oplossingen tegen de achtergrond van de verandering van het landgebruik, de voortdurende afhankelijkheid van de invoer in Europa en de bijkomende milieueffecten. Daarnaast worden discussies gevoerd over de economische aspecten van synthetische brandstoffen in vergelijking met het gebruik van aardgas met behulp van CCS, met name voor wat betreft de koolstofcyclus en de logistiek hiervan.

In dit proefschrift worden grote emissiebronnen, die niet door middel van brandstofvervanging kunnen worden aangepakt, geïdentificeerd en gekwantificeerd. Het gebruik van een bepaald aandeel cokes is in moderne hoogovens noodzakelijk en hoogovens zijn vereist om de door de moderne samenleving gevraagde hoogwaardige staalsoorten te kunnen leveren. Het vervangen van cokes (en kolen) betekent dus het vervangen van de hoogoven en hiermee een volledig energie-“ecosysteem”. De bijbehorende beslissingen zijn van strategische aard en niet toegankelijk met het in dit proefschrift ontwikkelde brandstofvervangingsmodel. Terwijl demonstratie-installaties voor alternatieve productieprocessen (bijv. directe reductie op basis van waterstof) in aanbouw zijn, wordt de grootschalige inzet ervan hier pas in 2030[113] in overweging genomen. Bovendien worden de emissies van verschillende processen niet beïnvloed door brandstofschakelaars. De meest relevante bron wordt gevormd door kalksteencalcinatie, toegepast in de cement- en kalkproductie. Omdat CO2 een noodzakelijk afvalproduct van klinkerverbranding is, vormen materiaalefficiëntie, toereikendheid en nieuwe cementsoorten de meest veelbelovende opties voor de vermindering van de BKG-uitstoot in deze sector. Al deze opties vertonen aanzienlijke terugkoppelingen naar alle sectoren van de samenleving. Hoewel dit proefschrift hier niet op ingaat, biedt de benadering die hier wordt toegepast een uitgangspunt om de opties die in de industriesector aanwezig zijn, bijvoorbeeld in gekoppelde modelsystemen, in overweging te kunnen nemen.

Koolstofafvang en -opslag (CCS) vormt een relatief handige en vrijwel direct beschikbare optie. Gezien de beperkte tijd die nodig is om de klimaatverandering te beperken, kan deze zelfs noodzakelijk zijn. Uit dit proefschrift blijkt echter dat er relevante alternatieven bestaan voor de emissiereductie op korte termijn. CCS dient daarom slechts een overbruggings- of noodtechnologie te zijn en niet de centrale pijler van de BKG-emissiereductie-inspanningen te vormen. De grootste inspanningen moeten gericht zijn op het vermijden van broeikasgasemissies. Als ondersteunend element kan CCS echter in geselecteerde toepassingen zoals de productie van klinkers worden

[113] Hoewel de meningen over de haalbaarheid van hun inzet verschillen [15]; de eerste proefinstallaties zijn voorzien tot 2030 of zelfs 2025. Het effect op de Europese broeikasgasemissies wordt echter waarschijnlijk later relevant.

gebruikt. Wanneer hun emissies niet op een andere wijze kunnen worden vermeden, bijvoorbeeld door een verandering van grondstof, zullen zij waarschijnlijk het resterende BKG-budget in 2050 verbruiken (bijvoorbeeld met een reductiedoelstelling van 95%). De meest relevante processen in dit verband zijn de productie van kalk en klinkers, die dus een uitstekend voorbeeld zijn voor de toepassing van CCS [16]. Dit geldt ook voor andere broeikasgasemissie-intensieve processen in de ijzer- en staalproductie, raffinaderijen en basischemicaliën [17].

Vanuit methodologisch oogpunt toont deze dissertatie aan dat het mogelijk is om een discrete keuzebenadering op te nemen in een bottom-up-energiemodel voor de industriële sector. Deze methode werd vroeger vooral toegepast op consumentgerichte onderwerpen als particulier en openbaar vervoer of op industriële toepassingen met een beperkte reikwijdte. Daarnaast zijn in het proefschrift twee benaderingen toegepast (revealed and stated preferences) om het model met parameters te onderbouwen en zodoende te operationaliseren. Deze voorkeuren waren voorheen niet beschikbaar en het proefschrift laat zien dat zij zowel op nationaal als op Europees niveau met een redelijke inspanning kunnen worden verworven. Dit vormt een vereiste voor de toepassing van de aanpak. De verbreding van het beeld, de scriptie en het werk dat tijdens de totstandkoming ervan is verricht, dragen bij aan beleidsadviezen met betrekking tot de energietransitie, de beperking van de klimaatverandering en de daarmee samenhangende beleidsvorming, door middel van kwantificering van het broeikasgasemissiereductiepotentieel van geselecteerde beleidsmaatregelen (energiedragerspecifieke subsidies en CO2-prijsstelling).

8.4 Aanbevelingen voor verder onderzoek

Dit proefschrift richtte zich op energie-intensieve industrieën en de processen met de hoogste emissies, omdat deze het meest relevant zijn voor een grootschalige emissiereductie. Hoewel verschillende kleinere processen ook in de analyse zijn opgenomen, moet de inspanning worden opgevoerd om de eigenschappen en mogelijkheden ervan gedetailleerder weer te kunnen geven. Dit geldt met name wanneer hun sectoren van strategisch belang zijn in diepgaande emissiereductiescenario's. Voorbeelden hiervan zijn voedselproductie, textiel, houtproductie, mijnbouw (vanwege het landgebruik), machines en voertuigproductie (vanwege hun belang in de Duitse en Europese economie). Deze processen zijn meestal heterogeen en talrijk, hetgeen een aanvullende uitdaging vormt voor de modellering. Dit geldt ook voor de toevoeging van locatiespecifieke informatie, die aanvullende uitdagingen en mogelijkheden voor de overschakeling op andere brandstoffen aan het licht kan brengen. Verdere analyse kan dan betrekking hebben op nieuwe bedrijfsmodellen en organisatiestructuren (bijv. energiecontracten, kleine energienetten, warmtenetwerken) en de gevolgen hiervan voor het brandstofvervangingspotentieel.

Het potentieel voor het overschakelen op andere brandstoffen in bestaande installaties is aanzienlijk en het kan een snelle emissiereductie opleveren. Uiteindelijk is dit echter niet voldoende om de vereiste emissiereducties tot 2050 te realiseren. Het is dan ook duidelijk dat na 2030 vergaande emissiereducties moeten worden bereikt, met nieuwe processen die een grotere inspanning en vervanging van volledige productieketens vergen. Dit omvat het directe gebruik van elektriciteit, het gebruik van waterstof (als energiedrager en grondstof) en CCS in geselecteerde toepassingen. Op dit moment ontbreken robuuste economische gegevens over veel van deze technologieën[114]. Zij zijn dus moeilijk op te nemen in endogene modelberekeningen, bijvoorbeeld als concurrentie voor conventionele productietechnologieën. De exploitatie van de eerste demonstratie-installaties in het komende decennium biedt wellicht de mogelijkheid om dit te doen. Toch is de wisselwerking tussen korte- en lange-termijnmaatregelen onduidelijk: ondersteunen de korte-termijnopties de overgang naar nieuwe processen of creëren zij nieuwe lock-in-effecten? Bij het opstellen van een stappenplan met het oog op onmiddellijke actie en het vooruitzicht op 2050 kunnen ongewenste paden worden aangegeven en kunnen vraagtekens worden gezet bij het potentieel van brandstofschakelaars. Tot slot wordt de interactie met de infrastructuur in dit proefschrift niet onderzocht, maar is deze van toenemend belang voor het gebruik van netgebonden energiedragers zoals elektriciteit, stadswarmte en aardgas.

De in dit proefschrift beschreven brandstofvervanging is geïntegreerd in een sectoraal bottom-up-model. Het bevestigde echter de wijdverbreide opvatting dat de interactie tussen de economische sectoren, met name de transformatiesector, van groot belang zal zijn. Een wisselwerking tussen de

114 Met de beste ervaringen in CCS [16] en directe elektrificatie van stoomsystemen, maar beperkte kennis over de prestaties van innovatieve productieprocessen [18]. Het Innovatiefonds [19] dat momenteel door de Europese Commissie wordt ingezet, kan de gegevensbasis verbeteren. Momenteel worden projecten voor de ontwikkeling van innovatieve productieprocessen geëvalueerd.

verschillende vraagsectoren en energiedistributie en -aanbod zal nodig zijn om vragen te beantwoorden die verband houden met een vergaande emissiereductie. De endogene modellering van innovatieve processen vereist ook de representatie van nieuwe, en potentieel dynamische, sectoroverschrijdende materiaal- en energiestromen. Zij beïnvloedt het gehele systeem en omvat strategische beslissingen. Het modelleren hiervan is niet vanzelfsprekend voor de myopische benadering waarvoor in dit proefschrift werd gekozen, voor een geleidelijke overschakeling op andere brandstoffen. Verder onderzoek dient zich te richten op de "service" van een product en dynamische verschuivingen van materiaalstromen en procesroutes mogelijk maken.

In dit proefschrift zijn modelparameters (geopenbaarde en aangegeven voorkeuren) voor brandstofschakelingen afgeleid, die niet eerder beschikbaar waren. Hoewel zij werken en aannemelijke resultaten opleveren, zou het nuttig zijn om deze resultaten met verschillende methoden te reproduceren, rekening houdend met meer verfijnde kwantitatieve analyses (geopenbaarde voorkeuren). De geselecteerde periode kan worden uitgebreid met het effect van de economische crisis in 2008, om reacties op vraagschokken op het gedrag van brandstofschakelaars af te leiden. Bovendien bleek uit het proefschrift dat de modelparameters minder betrouwbaar zijn voor kleine landen van de EU28, hetgeen ook kan worden verbeterd met behulp van gedetailleerde analyses hiervan. De aangegeven voorkeuren kunnen worden uitgebreid met aanvullende technologieën en een groter aantal deelnemers, door zich te richten op meer landen in de Europese Unie. Dit zou enerzijds de analyse van subsectoriële voorkeuren mogelijk maken, maar anderzijds ook ons inzicht in de marktkansen voor bijvoorbeeld hoge-temperatuurwarmtepompen, waterstof en direct elektriciteitsverbruik verbeteren.

De in de vorige paragrafen gepresenteerde "verlanglijst" zal niet in één enkel model worden uitgevoerd. Daarom zal de interactie tussen modellen toenemen. Er moeten inspanningen worden geleverd om de afzonderlijke modellen open te stellen voor anderen en transparante en veelzijdige modelinterfaces te creëren. Tegelijkertijd moet de complexiteit van de modellen die in beleidsadviezen worden toegepast, worden verminderd. Het vormt een ongemakkelijk gegeven dat de kennis over de toegepaste modellen voor beleidsadvisering met een grote impact op de samenleving slechts op enkele ontwerpers van modellen is geconcentreerd en moeilijk te verspreiden is. Dit zou kunnen worden verholpen door het bewust verwijderen van modelonderdelen die niet (in hun volle complexiteit) met regelmatige tussenpozen nodig zijn, waardoor de kernelementen die vereist zijn om de respectievelijke onderzoeksvragen te beantwoorden, worden geconcentreerd. Hierdoor zou een levensvatbare weg naar open source-modellen kunnen worden gecreëerd en de transparantie en daarmee de geloofwaardigheid, maatschappelijke impact en toepasbaarheid van de energiesysteemmodellen en de hierop gebaseerde beleidsadviezen kunnen worden verbeterd.

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Curriculum Vitae

Matthias Rehfeldt completed the Bachelor and Master program in "Mechanical Engineering - Renewable Energies" at the Beuth University of Applied Sciences in Berlin with special focus on energy economy and mechanics. He finished his Bachelor thesis titled "Investigation of mechanical load profiles on solar-thermal collectors based on field- and test-station measurements under consideration of relevant inspection- and design norms" at the Fraunhofer ISE in Freiburg and his Master thesis titled "Identification of waste-heat use and fuel-switch potentials in energy-intensive industrial processes" at the Fraunhofer ISI in Karlsruhe. He obtained his "Master of Engineering" in June 2014.

Continuing his work at the Fraunhofer ISI, Matthias Rehfeldt joined the "Helmholtz Research School on Energy Scenarios (ESS)" in March 2015, where he attended a post-graduate qualification program. In parallel, he started the work on his dissertation at the University of Utrecht. During his time at the Fraunhofer ISI, he worked on and co-authored several national and European research and policy advice projects.

Anthropogenic climate change is one of the greatest challenges of this century: The consequences of global warming above 1.5°C seriously threaten our civilization. Climate scientists thus agree that the release of greenhouse gases (GHG) to the atmosphere must be reduced by about 50 % until 2030 and reach net-zero until 2050. The manufacturing industry is one of the main emitters of GHG in the European Union. This is caused by its reliance on fossil fuels as energy carrier and feedstock. This thesis investigates opportunities for important industrial processes to switch to less GHG-intensive energy carriers. The analysis incorporates technical, economic and behavioural aspects of energy carrier selection. The insights gained inform a bottom-up energy system model, which is used for policy advice on national and European level. One of the main conclusions of this thesis is that vast technical potentials for fuel switching exist and that it may be a substantial pillar of early decarbonisation. The realization of these potentials however requires drastic changes to economic conditions.

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