# Model based evaluation of industrial greenhouse gas abatement measures using *SmInd*

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**Abstract:** Due to the heterogeneity and complexity of the industry sector the holistic analysis of possible transformation pathways requires a model-based approach. In this publication, the core elements of the sector model *SmInd* are explained before it is applied to evaluate a *low-hanging fruits electrification* scenario for Germany until 2050. SmInd is designed as a modular stock and flow model, combining both bottom-up and top-down modeling approaches. In its current state SmInd covers 14 industry sub-sectors including cross-sectional technologies, 22 bottom-up processes and 9 energy carriers. In this paper, a high efficiency reference scenario is expanded to include low temperature process heat electrification measures and process substitution measures for the steel and glass manufacturing industry. The scenario results show that full electrification in the considered areas is achieved before 2050. By 2050, electrification results in a 37 % reduction of final energy consumption through fossil fuels and a 26 % increase in electricity consumption, compared to the *only efficiency* reference scenario. Electrification including efficiency benefits from the reference scenario leads to a 74 % reduction of energy-related industrial greenhouse gas emissions until 2050, compared to 1990.

**Keywords:** Electrification, Sector model, Demand-side electrification, Power-to-heat, Energy system transition, Cost of electrification, Industry, Greenhouse gas abatement

## 1 Introduction

By defining sector specific greenhouse gas (GHG) emission reduction goals for 2030, the *German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)* issued a further layer of detail to Germany's extensive set of climate policy goals [1]. This set of goals signals that every energy end-use sector is required to commit to GHG emission reduction efforts, in order to achieve the most important climate policy goal: 95 % GHG emission reduction until 2050, with respect to 1990. Consequently, also the German industry sector is required to reduce its direct GHG emissions by 51 % until 2030, with respect to 1990. This is equivalent to emissions of 70 Mt of $CO_{2\text{-eq.}}$ in 2030 [2] and translates to a ca. 95 % reduction until 2050.

To achieve deep decarbonization in the heterogeneous and complex industry sector a combination of GHG abatement measures is required (e.g. energy efficiency, electrification, carbon capture and storage). Depending on the selected transformation path, the systemic effects of the industrial energy transition as well as the costs resulting from the implementation of decarbonization measures can vary significantly. Due to the high number of possible pathways and the complexity of the industry sector, a model based approach is required to analyze the long term effects of measure implementation. In this paper the fundamental

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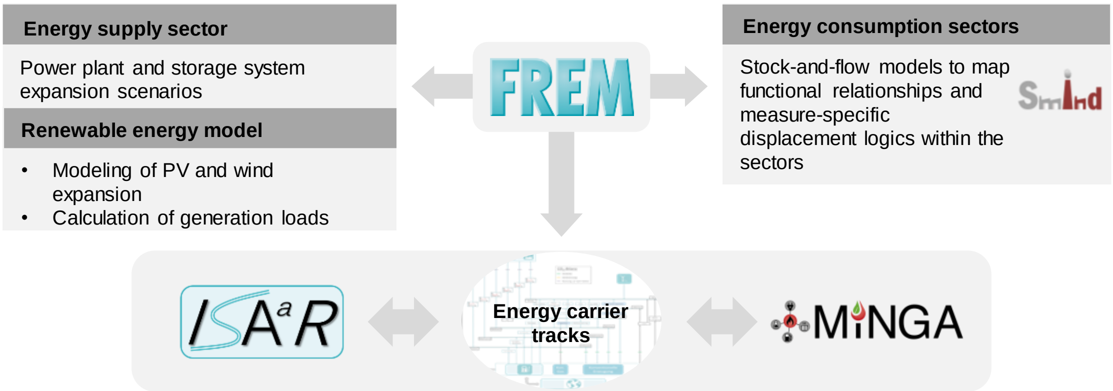
principles of the sector model industry (SmInd) are explained. Ultimately exemplary model results are discussed for a low-hanging fruits electrification scenario in the German industry sector.

The structure of this paper follows the necessary steps required to derive a model-based evaluation of the low-hanging fruits electrification scenario. Section 2 explains the basic modelling approach as well as the input data. Section 3 focuses on the development of the industry model and is subdivided according to the defining elements of SmInd. The latter are the industry structure (3.1), measure implementation (3.2) and the synthetic load profile (3.3) modules. In section, 4 the low-hanging fruits electrification scenario is introduced (4.1) and model results are discussed (4.2). The limitations of the approach, ideas for further research and the conclusion are presented in section 5.

# 2 Modeling the industry sector – the SmInd approach

The aim of SmInd is the scenario-based evaluation of the industrial final energy consumption (FEC) and GHG-emissions, between 2015 and 2050. SmInd is designed as a modular stock and flow model, combining both bottom-up and top-down modeling approaches [3]. It is embedded in the FfE[2] model landscape according to Figure 1.




ISAaR – Integrated Simulation Model for Planning the Operation and Expansion of Power Plants with Regionalization
MiNGA - Market- and Infrastructure model of the Gas sector

*Figure 1: Connection of SmInd to the energy system model (ISAaR) and gas market model (MINGA) via the database FREM*

The figure shows the central element FREM[3] which connects SmInd to the energy system model ISAaR[4] and the gas market model MINGA[5]. Through this connection, the effects of measure implementation in the industry sector on the energy supply side can be analyzed. Hereby, SmInd provides load and emission data and receives emission factors and energy

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[3] FREM is a PostgreSQL database. Cf. [23] for details.

[4] ISAaR – Integrated Simulation Model for Planning the Operation and Expansion of Power Plants with Regionalization. Cf. [36] for details.

[5] MINGA - Market- and Infrastructure model of the Gas sector. Cf. [37] for details.

prices. By coupling SmInd to supply-side models the effect of system repercussions on measure implementation in the industry sector can be evaluated.

The structure of SmInd is influenced by aspects such as:

- the statistical definition of the industry sector according to [4],
- the availability of reliable data
- and the tradeoff between respecting the heterogeneity and complexity of industrial processes whilst achieving full coverage of the industry sector in model simulations.

The three core building blocks of the MATLAB based SmInd are the modules *industry structure*, *greenhouse gas abatement measures* and *synthetic load profiles*. Each module contains one or more sub-modules and is constructed so that further elements can be added in future. Table 1 summarizes the data sources and type for each SmInd module. An overview of the data and functionality of each module is provided in this section. The methodology for modelling these modules is explained in section 3.

*Table 1: SmInd data sources and types*

| | ***Industry structure*** | | ***GHG-abatement measures*** | | ***Synthetic load profiles*** | |
|---|---|---|---|---|---|---|
| Level of detail | Sub-sector specific | Process specific | Process specific | Cross-sectional | Process specific | H&HW |
| Data source | Literature review, statistics | | Primary data from energy audits, literature review, statistics, interviews | | primary data from energy audits, statistics | |
| Data type | Energy application balances Germany; Energy consumption by temperature levels and industry branch | | Technology data: lifetime, cost, exchange rate, application factor, efficiencies and interdependencies | | Electricity and gas load curves | |
| | Emission factors; Energy prices | Specific energy consumption; Production tonnage | Production tonnage | No. of businesses | | |

*H&HW = Heating and hot water

***Industry structure:*** Figure 2 shows the basic setup of the industry structure in SmInd. The FEC of emission intensive processes is modeled bottom-up using the production tonnage and specific FEC per ton of product. The process selection is based on an application related emission balance for the industry sector [2] and is described in [5]. The production tonnage and specific FEC per ton of product are literature values, which have been validated by industry experts. GHG abatement measures are defined process step specific for all processes which are modeled bottom-up. Less energy intensive processes as well as cross-sectional technologies (CST) such as lighting, electric motors, etc. are modeled top-down. The energy consumption for these processes and CSTs is derived from energy application balances [6]. In SmInd also the supply of heating and hot water (H&HW) is modeled as a CST. The implementation of GHG abatement measures for CSTs is sub-sector unspecific.

For time-independent energy carriers (e.g. hard coal, lignite, coke, etc.) emission factors for calculating GHG emissions are taken from [7]. Time dependent emission factors for electricity, district heat, hydrogen and synthetic fuels are determined scenario specific based on iterative calculations according to cf. Figure 1. For the methodology used to determine process related emissions cf. [18]. The granularity of energy carriers modeled in SmInd corresponds to the energy carriers in [6] and is expanded by hydrogen and synthetic fuels [18]. In total SmInd covers 11 energy carriers.

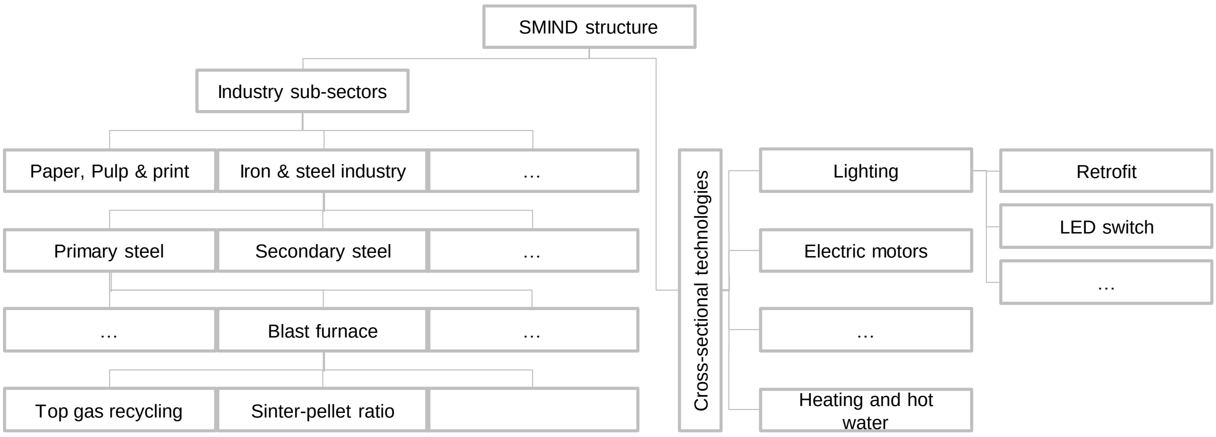


*Figure 2: SmInd structure for industry sub-sectors and cross-sectional technologies [8]*

Furthermore, the sub-sector specific FEC for process heat, which accounts for ~65 % (~1680 PJ in 2015) of total industrial FEC, is assigned to temperature levels. This adds another structural layer to the input data and allows for the assignment of GHG abatement measures to specific temperature levels. A variety of different temperature distributions for industrial process heat demand can be found in the literature (cf. for instance [9], [10], [11], [12]). The statistics differ according to the granularity of the temperature ranges and the definition of industry sub-sectors. For the calculation of Germany specific scenarios SmInd temperature level distribution is based on [9], as the industry sub-sector definition in this source is identical to that used in FEC statistics such as [6] or [13].

**Temperature levels in SmInd:** Due to the modular setup of SmInd and the fact that all input data is stored outside of the model, in the database FREM, the sub-division according to temperature levels can easily be adapted. Analyzing the effect of using different temperature statistics on the implementation of GHG abatement measures poses an idea for further research.

**Greenhouse gas abatement measures:** SmInd currently contains two GHG abatement *measure clusters*: *process specific* and *CST measures* (cf. Figure 2). For each measure cluster different GHG abatement *measure types* such as *energy efficiency*, *fuel switch* and *process substitution* are defined. The diffusion of abatement measures is contingent upon the lifetime of the current technology stock, which is translated to an annual technology exchange rate.

The identification and quantification of process specific GHG abatement measures is described in detail in [5]. Hereby a variety of literature sources, industry sub-sector specific statistical databases and expert interviews build the basis for technology data, such as capital expenditure, operational expenditure, lifetimes, efficiencies, specific energy savings and the process measure application factor [5]. The latter defines the share of production tonnage for which an abatement measure is applicable.

The derivation of measures for CSTs and the associated technology data is based on primary data acquired in approximately 200 energy audits [19]. Cost data for CST abatement measures is supplemented by technology information sheets such as [15]. The CST measure application factors are based on expert estimates and are expressed as the share of companies in Germany [16], for which the CST measure is applicable.

For both cross-sectional and process measures, interdependencies concerning the abatement potential are considered in the input data. Measure interdependencies are expressed in the form of cross-measure impact matrices as developed and applied in [17] and further discussed in [5]. In cases where the quantification of interdependencies between two or more measures is not possible, the measure with the higher GHG abatement potential is modeled and the other measure(s) are excluded from the further analysis.

For details concerning the carbon capture and storage module cf. [18]. Further research is required to include circular economy, material efficiency and life cycle assessments as GHG abatement measures and evaluation possibilities in SmInd.

***Synthetic load profiles:*** SmInd delivers electricity and gas load curves to the supply side model ISAaR in order to evaluate the effect of industrial GHG abatement measure implementation on the power system (cf. Figure 1). These aggregated energy carrier specific load curves are based on normalized sub-sector specific synthetic load profiles for process heat, H&HW and electricity.

Basis for the development of normalized synthetic load profiles for the mentioned applications, energy carriers and 14 industrial sub-sectors is the raw data of measured load curves obtained in energy audits performed by the FfE [19]. The currently available raw data consists of 182 electricity and 74 process heat load curves and covers all sub-sectors except *Iron and steel*. For the latter a load profile is manually developed based on [20].

After an initial screening phase in which the load curves are checked for missing and negative values, the raw data serves as input data for a regression analysis. During the regression analysis the correlation of the load with selected regression parameters such as the monthly production index [21] is determined. Then, mean regression coefficients are calculated for each parameter in every sub-sector and processed further to derive normalized load profiles. The methodology used to determine synthetic load profiles is designed to allow a gradual improvement of the load curves, as additional raw data is collected over time.

# 3 SmInd Methodology

Section 2 describes the core modules of SmInd. Section 3 formalizes the basic structure of SmInd. In each section the influence of data availability and form on the setup of SmInd, is highlighted.

### 3.1 Industry structure

Driving forces behind the structure of SmInd are the resolution of energy consumption statistics in Germany and the form and availability of data required to model industrial processes and the relevant GHG abatement measures. A key challenge in modelling the industry sector is that not the entire demand structure can be modeled bottom-up. This results from the heterogeneity of the processes in this sector as well as the data availability. The industry structure is consequently modeled as a mix between top-down and bottom-up approach.

Expression (3-1) shows the energy application matrix, $\boldsymbol{EAM}$. The $\boldsymbol{EAM}$ is used to model the annual, $y$, share of FEC by energy carrier, $ec$, and application, $ap$, in each of the 14 industry branches, $ib$.[6] For a variety of industrial processes as well as process specific abatement measures, only aggregated values for the specific fuel and electricity consumption/savings are provided in the literature.[7] In order to determine the $CO_2$-emissions by process and the effect of measure implementation on $CO_2$-emissions, aggregated values for the fuel consumption are however insufficient. Consequently, the $\boldsymbol{EAM}$ is used to disaggregate the process fuel consumption and fuel savings resulting from measure implementation to energy carrier specific savings.

The $\boldsymbol{EAM}$ is derived from the structure provided in the energy application statistics [6]. Separate matrices are constructed for the energy carrier types, $ect$, electricity and fuel consumption. The sum of the percentage shares, $eam_{\boldsymbol{ec,ap}}$, in each matrix equals one.

$$\boldsymbol{EAM}_{\mathbf{ib,ect,y}} = \begin{pmatrix} eam_{11} & \cdots & eam_{1,ap} \\ \vdots & \ddots & \vdots \\ eam_{ec,1} & \cdots & eam_{ec,ap} \end{pmatrix}_{\text{ib,ect,y}} = 1 \qquad (3\text{-}1)$$

In its current configuration, SmInd operates based on the assumption that the shares in the $\boldsymbol{EAM}$ are only affected by the implementation of GHG abatement measures and do not undergo a natural shift. The energy consumption of CSTs as well as the differentiation of process heat according to temperature levels are modeled as separate applications in the $\boldsymbol{EAM}$.

**SmInd Europe (SmInd-EU)**: An idea for further research is the adaptation of the energy application matrix to allow SmInd calculations for other countries. Hereby the shares in the $\boldsymbol{EAM}$ need to reflect the energy consumption by application, energy carrier and sub-sector for the desired countries.

The annual FEC by energy carrier and application for each industry sub-sector, $fec_{ib,ec,ap,y}$, is determined by expression (3-2).

[6] Often referred to as industry sub-sectors.

[7] Cf. for instance SmInd measures for the chemical industry in [14].

$$\boldsymbol{FEC}_{\mathbf{ib,ec,ap,y}} = fec_{ib,ect,y} \cdot \boldsymbol{EAM}_{\mathbf{ib,ect,y}} \quad (3\text{-}2)$$

$fec_{ib,ect,y}$ can be affected by GHG measure implementation as well as through exogenous assumptions concerning the energy consumption in the industry sector.[8] Values for the total FEC by energy carrier or application in each industry branch can be derived by aggregating the respective columns or rows of the matrix, $\boldsymbol{FEC}_{\mathbf{ib,ec,ap,y}}$. The latter contains the absolute energy consumption by energy carrier and application for each industry branch.

In order to determine annual emissions in the industry, the FEC by sub-sector and energy carrier, $fec_{ib,ec,y}$, is disaggregated into hourly values, $t$, using sub-sector load profile vectors, $\boldsymbol{lp_{ib,ec,ap,t}}$. Hereby, SmInd uses the 2016 load profile for all years until 2050. Due to the availability of load data (see section 3.3) currently three different types of load profiles are differentiated in every sub-sector:

1. Electricity load profile: used to model the timely distribution of the electricity consumption, independent of the application
2. Fuel process heat load profile: used to model the timely distribution of all fossil energy carriers used for process heat and mechanical energy
3. H&HW load profile: Used to model the timely distribution of electricity and fuel consumption for H&HW.

Annual industrial emissions, $EM_y$, are derived using expression (3-3).

$$EM_y = \sum_{ib}\sum_{ec}\sum_{t}((fec_{ib,ec,y} \cdot \boldsymbol{lp}_{\mathbf{ib,ec,ap,t}}) \circ \boldsymbol{emf}_{\mathbf{ec,y,t}}) = \sum_{ib}\sum_{ec}\sum_{t}(\boldsymbol{lc}_{\mathbf{ib,ec,y,t}} \circ \boldsymbol{emf}_{\mathbf{ec,y,t}}) \quad (3\text{-}3)$$

Hereby the load curve vector, $\boldsymbol{lc}_{\mathbf{ib,ec,y,t}}$, results from the multiplication of $fec_{ib,ec,y}$ with each element in the load profile vector, $\boldsymbol{lp}_{\boldsymbol{ib},\mathbf{ec,ap,t}}$. The Hadamard product of $\boldsymbol{lp}_{\mathbf{ib,ec,t}}$ and the emission factor vector, $\boldsymbol{emf}_{\mathbf{ec,y,t}}$, yields a vector with hourly absolute $CO_2$-emissions. The sum of these vectors over each sub-sector and energy carrier results in the annual total energy-related emissions of the industry sector.

As SmInd is a hybrid model, a share of the energy consumption in each sub-sector is determined bottom-up, $bu$. The total annual final energy consumption for fuel and electricity covered by processes that are modeled bottom-up, $fec_{bu,ect,y}$, is calculated using expression (3-4).

$$fec_{bu,ect,y} = \sum_{ip}\sum_{ec} fec_{ip,ec,y} = \sum_{ip}\sum_{ec}(sec_{ip,ec,y} \cdot pt_{ip,y}) \quad (3\text{-}4)$$

[8] For instance: it is possible to assume values for the FEC based on other studies.

The FEC of an industrial process, $fec_{ip,ec,y}$, is derived from its specific energy consumption, $sec_{ip,ec,y}$, and production tonnage, $pt_{ip,y}$. SmInd currently covers 22 process routes, which account for ~50 % of industrial energy related $CO_2$-emissions in 2015.[9] In order to avoid double balancing of energy consumption, the sub-sector bottom-up energy consumption, $fec_{bu,ect,y}$, is deducted from the total sub-sector energy consumption at the beginning of each year. If an external scenario is used to fix values for the sub-sector final energy consumption, $FEC_{ib,y}$, and the production tonnage, $pt_{ip,y}$, the specific energy consumption values, $sec_{ip,ec,y}$, of the bottom-up processes are adapted according to the change in FEC in each industry branch. This avoids the probability of bottom-up energy consumption being higher than the industry sub-sector FEC. On top of this, measure implementation can lead to changes of the specific energy consumption.

## 3.2 Implementation of GHG-abatement measures

The implementation methodology for GHG-abatement measures in SmInd depends on the GHG measure type, the measure cluster and the share of the energy consumption that is covered using bottom-up data in the respective sub-sector. The SmInd cube in Figure 3 shows possible combinations for the three criteria.

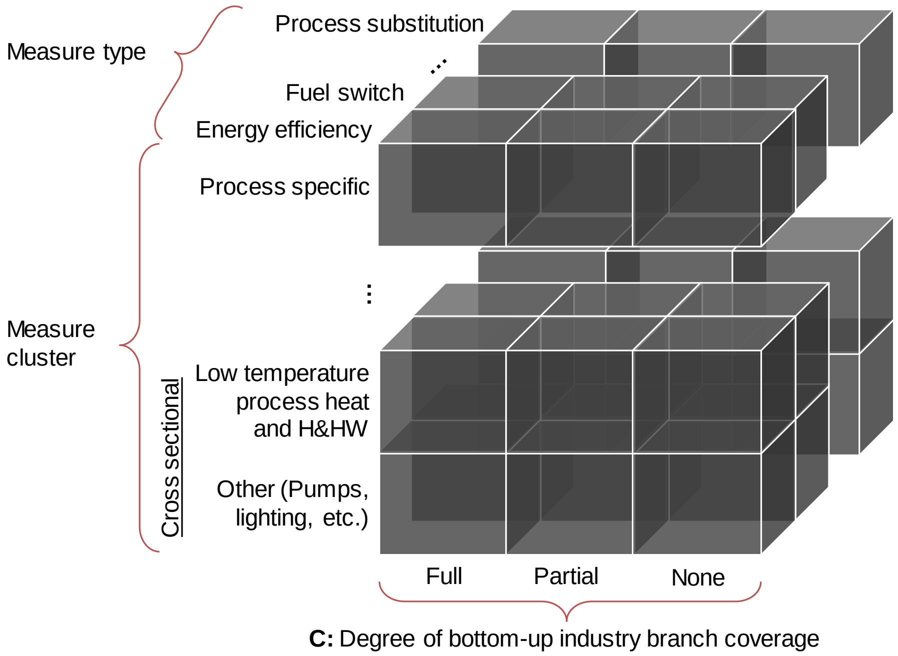


*Figure 3: Possible combinations of GHG-abatement measures by cluster and bottom-up industry branch coverage*

In this section each of the dimensions of the SmInd cube are explained.

[9] The modeled processes are: pulp, paper, cement, lime, brick, primary steel, secondary steel, directly reduced iron steel, aluminum, container glass, flat glass, milk, ammonia, ethylene, chlorine, methanol und polyethylene. For steel, cement, lime and glass several production routes are modeled.

### 3.2.1 Measure cluster

The measure cluster defines the share of energy consumption that is affected by the implementation of a GHG abatement measure. A measure falls into the process specific cluster if its implementation affects the energy consumption of a process, which is modeled bottom-up in SmInd. The cross sectional cluster indicates that measure implementation is process unspecific and does not differ according to the sub-sector. The CST cluster is sub-divided into *Low temperature process heat and H&HW* and *Other*. Through the definition of temperature levels as applications in the $\boldsymbol{EAM}$ (see section 3.1) it is possible to define cross sectional measures for different process heat levels.[10] Measures for H&HW are modeled as cross-sectional measures, as it is assumed that the supply of H&HW is similar across the industry sub-sectors. Each measure type can occur in every measure cluster.

### 3.2.2 Measure type

While the measure clusters show which part of the industrial energy consumption is affected by the respective GHG abatement measure, the measure type indicates which logic is applied for measure implementation.

**Energy efficiency measures**

The methodology applied for energy efficiency measures is independent of the measure cluster. For simplicity, the methodology is explained with reference to process specific measures. Where necessary adaptations for CST measures are discussed.

Annual total energy savings per process, $tes_{ip,y}$, are defined under consideration of the annual energy savings per measure, $es_{m,y}$. The energy savings per measure are defined by its specific energy savings, $ses_{ip,m,ec,y}$, the annual production tonnage of the respective process, $pt_{ip,y}$, the application factor, $af_{ip,m}$, and the annual exchange rate, $er_{m,l}$ [5]. For CST measures, the number of businesses in which a certain CST exists, is used in analogy to the production tonnage for process measures.

$$es_{m,y} = \sum_{ec} \left( ses_{ip,m,ec,y} \cdot pt_{ip,y} \cdot af_{ip,m} \cdot er_{m,l} \right) \tag{3-5}$$

Due to a lack of data showing the age structure of industrial technologies the maximum annual exchange rate is approximated using expression (3-6) where, $l$, is the lifetime of the affected technology stock.

$$er_{m,l} = \frac{1}{l_{stock}} \tag{3-6}$$

[10] For example: some of the modeled electrification measures affect the energy consumption for low temperature process heat and are not differentiated according to sub-sectors.

Hence, measures are implemented at the end-of-life of the technology stock. In terms of the calculation of measure cost, this assumption prohibits the exchange of technologies with a residual value.

SmInd measure implementation for energy efficiency measures operates using measure bundles. In its current state SmInd uses data for approximately 90 process specific efficiency measures [5]. For each process the associated measures are bundled by aggregating the specific energy savings and calculating average application factors, $\emptyset af_{ip,m}$, and measure lifetimes, $\emptyset er_{m,l}$. This allows for a simplified depiction of model results. Interdependencies of the measures within a bundle and between bundles are considered through an appropriate definition of the input data according to [17] and [5]. The total annual energy savings of a process are consequently calculated by expression (3-7).

$$tes_{ip,y} = \sum_{ec}\left(pt_{ip,y} \cdot \emptyset af_{ip,m} \cdot \emptyset er_{m,l} \cdot \sum_{m} ses_{ip,m,ec,y}\right) \quad (3\text{-}7)$$

## Fuel switch

In SmInd, fuel switch measures are defined as CST measures and are therefore process unspecific. These measures affect the FEC for H&HW and process heat within a certain temperature range. For instance: low-temperature electrification measures such as the substitution of oil or gas boilers through heat pumps and electrode boilers are modeled as fuel switch measures in SmInd. See [18] for details concerning the implementation of fuel switch measures for synthetic fuels.

The methodology for fuel switch measures is derived in analogy to the electrification methodology described in [24]. For these measures, a process unspecific reference and substitution technology are defined, to model the changes in energy consumption and the associated costs. The potential of fuel switch measures equals the fossil FEC in the respective temperature range.[11] Expression (3-8) shows the total additional electrical FEC, $fec_{elec,y}$, resulting from fuel switch electrification measures in SmInd.

$$fec_{elec,y} = \sum_{T}(fec_{fuel,T,y} \cdot \frac{\eta_{ref,T}}{\eta_{elec,T}} \cdot af_{elec,T} \cdot er_{ref,l}) \quad (3\text{-}8)$$

Hereby, the quotient of the energy conversion efficiency, $\eta$, between the fossil reference technology, $ref$, and the electrical technology, $elec$, defines the ratio between displaced fossil FEC, $fec_{fuel,T,y}$, and additional electrical FEC, $fec_{elec,T,y}$, within a temperature range $T$. The application factor, $af_{elec,T}$, results from constraints with respect to the implementation of the electrical technology at the respective temperature level. The maximum exchange rate, $er_{ref,l}$,

[11] Electrically and renewably powered appliances are excluded from the measure potential.

is defined in analogy to expression (3-6) and depends on the lifetime of the fossil reference technology.

**Process substitution**

The substitution of process routes (e.g. shift of primary to secondary steel production) is a process specific measure, which is modeled as a shift of production tonnage from one process to another. The resulting changes in FEC are derived using expression (3-4). In analogy to the energy efficiency and fuel switch measures, an application factor and maximum annual exchange rate are defined. The latter is defined with respect to the technical lifetime of the process that is being replaced. Process substitution measures implemented in SmInd currently include measures leading to a displacement of fossil fuels and resulting in additional electricity, synthetic fuel or hydrogen demand [18].

### 3.2.3 Degree of bottom-up industry branch coverage:

The third dimension shown in Figure 3 addresses the *degree of bottom-up industry branch coverage*. In SmInd, efficiency measures are only defined for processes which are modeled bottom-up according to expression (3-4). If the energy consumption of a sub-sector is fully explained by bottom-up processes, changes in energy consumption and the associated costs in this sub-sector result directly from the quantified decarbonization measures, according to expression (3-9). In order to model the entire industry sector, a simplified approach for the sub-sectors with partial and bottom-up coverage is required. For both cases it is assumed that the quantified measures can be used as an indicator for the specific energy saving potential and associated costs in other sub-sectors. For partial coverage, expression (3-10) and no coverage, expression (3-11) is used.

Full coverage
$$tes_{ib,y} = \sum_{ip} tes_{ib,ip,y} \tag{3-9}$$

Partial coverage
$$tes_{ib,y} = \frac{\sum_{ip} tes_{ib,ip,y}}{fec_{bu,ip,y}} \cdot (fec_{ip,y} - fec_{bu,ip,y}) + tes_{ip,y} \tag{3-10}$$

No coverage
$$tes_{ib,y} = \sum_{ip} (\frac{tes_{ib,ip,y}}{fec_{bu,ip,y}} \cdot (fec_{ip,y} - fec_{bu,ip,y}) + tes_{ip,y}) \tag{3-11}$$

In the case of partial or no coverage, the same logic applies: the share of energy saving per unit of energy consumption for the bottom-up covered processes, $\frac{\sum_{ip} tes_{ib,ip,y}}{fec_{bu,ip,y}}$, is calculated. This share is then applied to, $(fec_{ip,y} - fec_{bu,ip,y})$, which shows the energy consumption not explained by bottom-up modelling.

## 3.3 Synthetic load profiles

As described in section 2, SmInd delivers load curves to the energy system model ISAaR in order to determine the system effects of GHG abatement measure implementation in the industry sector. Figure 4 shows the approach used to determine sub-sector load profiles in

SmInd. Input data are measured electrical and fuel load curves obtained in energy audits performed by the FfE [19]. The procedure is explained for the derivation of process heat load profiles.

In a first step, the raw input data is prepared for the subsequent regression analysis. The load curves are anonymized, assigned to the respective sub-sector and missing and negative values are corrected. If the raw data includes FEC for process heat and H&HW, the H&HW components are removed.[12]

For the subsequent linear regression analysis, it is assumed that process heat load profiles are independent of outside weather conditions and solely dependent on the monthly production index [21]. The first step of the regression analysis is the assignment of the input load curves to the state and district where they were measured. Subsequently each hourly interval is assigned to a *type of day* (Mo, Tue-Thurs, Fr, Sa/bridge day, Su/holiday). In the regression analysis, a regression coefficient and $R^2$ value is calculated for each hour of a certain *type of day*, which shows the dependency of the load curve with respect to the monthly production index. In total 120 regression results are calculated per load curve.

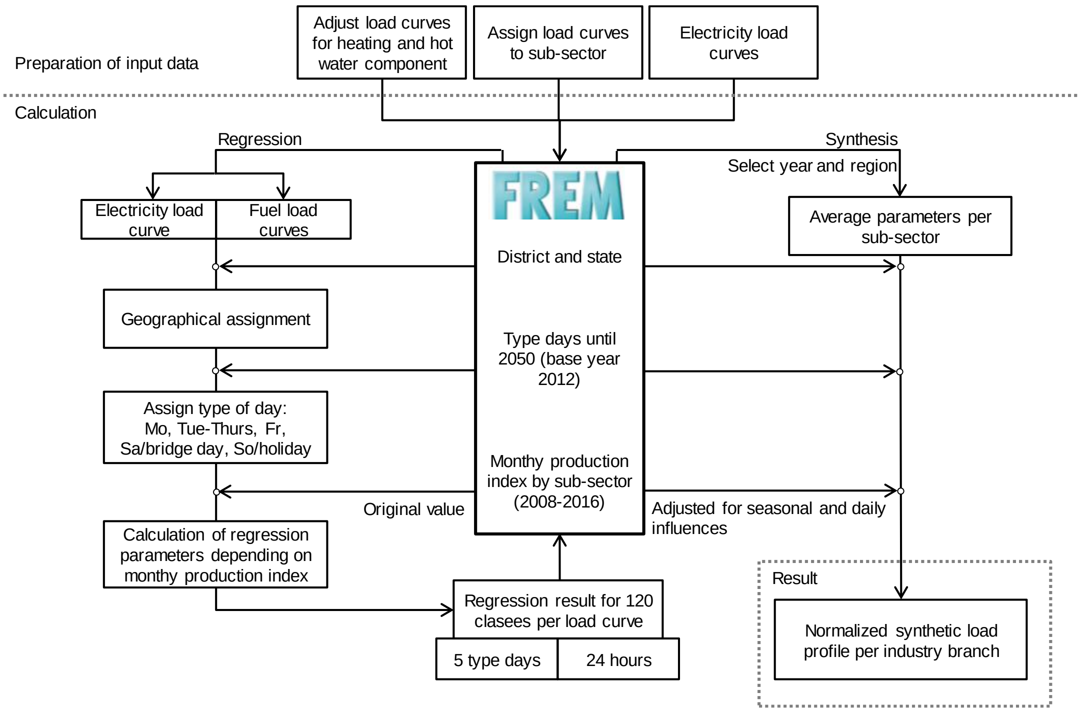


*Figure 4: Flow chart showing the steps for creating synthetic industrial load curves*

The resulting regression parameters are averaged to derive a reference load profile for each industry sub-sector.[13] Currently the *type of days* for all load profiles are based on the year 2012 as this is the base year for calculation in the energy system model ISAaR. The sub-sector specific regression results are then multiplied by the respective monthly production index and the regression constants are added. In a last step, the sub-sector load profiles are normalized. SmInd uses the 2016 load profile for all years until 2050.

[12] A seperate H&HW load profile is derived based on 12 pure H&HW load curves.

[13] If several load curves from one company serve as input data, first a company reference load profile is calculated.

# 4 Low hanging fruits electrification scenario

The model structure described in section 3, enables SmInd to calculate scenario results on three different levels:

- Effect of individual measures
- Analysis at process level
- Analysis at industry branch level

On each of these levels results can be presented in the following ways:

- Emissions by industry branch, process and energy carrier
- Energy consumption by process, industry branch and energy carrier
- Change in production tonnage (process level only)

The granularity of the energy carriers and applications is based on [6]. The energy carriers Hydrogen and synthetic fuel have been added [18]. The applications have been expanded by including different temperature levels according to [9]. In this section, first, the reference and electrification scenario is outlined and secondly, SmInd results are discussed.

## 4.1 Scenario description

The scenario analysis focuses on the greenhouse gas reduction that a *low-hanging fruits* electrification scenario can yield, if implemented in addition to the measures in the reference scenario in [25]. The reference scenario in [25] fails to achieve the climate goals until 2050, but can be considered an ambitious reference scenario in which mainly efficiency measures are implemented in the industry sector. The implementation of electrification measures is negligible. As [25] does not provide process specific production volumes and energy consumption values, production figures from [26] are implemented in this scenario to approximate the consumption of processes which are modeled bottom-up.

In the electrification scenario, low temperature process heat and H&HW are electrified. Furthermore, process substitution measures are implemented. The latter are restricted to the measures *primary to secondary steel making* and *fossil flat and container glass to electrical flat and container glass*. As argued in [24], [27], [38] and [28] electrification is technically possible in these areas. No further efficiency measures are implemented beyond the efficiency gains resulting from electrification and those already implemented in the reference scenario.

Due to the definition of fuel switch measures in SmInd, electrification occurs in all sub-sectors with fossil FEC in a temperature range below 240 °C. Hereby an industrial heat pump (coefficient of performance 3.5) is used in the temperature range below 100 °C and an electrode boiler (degree of utilization 99 %) between 100 °C and 240 °C [29]. Each electrical unit displaces an average fossil industrial boiler (Degree of utilization 97 %) which is defined using data from [19]. For further technical details and parameters concerning the implemented electrical technologies confer [24] and [5].

The substitution of primary through secondary steel is defined according to [30] and replaces all components in a primary steel making plant through a scrap fired electric arc furnace. The maximum share of electrical steel compared to total steel production is set to two thirds of the 2015 production volume [31]. No technical limits are assumed for the substitution of container and flat glass through electrical glass [38]. For further details concerning the technical parameters confer [24] and [5].

The implementation of electrification measures starts in the year 2021 and ends in 2050. However, it is assumed that electrification occurs at the maximum annual exchange rate (see section 3), which depends on the lifetime of the existing infrastructure [24]. Measure implementation can therefore end before 2050, if the electrification potential is exhausted before this point in time. While not all technical electrification potentials in the industry sector are realized in this scenario, it should still be considered ambitious due to the high annual exchange rates.

## 4.2 Results

The changes in energy related emissions, energy consumption and production tonnages resulting from the *low-hanging fruits* electrification scenario are analyzed with respect to the high efficiency reference scenario based on [25].[14] Figure 5 to Figure 8 show selected results for the reference and electrification scenario.

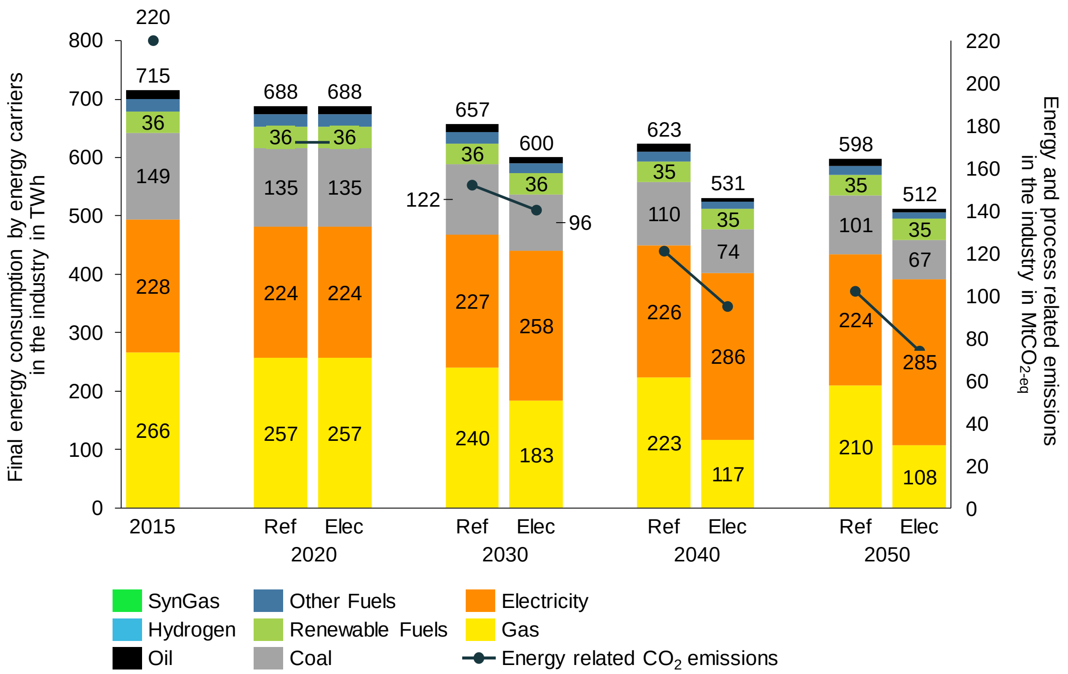


*Figure 5: Final energy consumption by energy carrier (in TWh) and energy related emissions (MtCO$_2$) in the industry sector for the reference and electrification scenario (2015 – 2050)*

Figure 5 shows that the implementation of electrification measures leads to an additional reduction of 80 MtCO$_2$ of energy related GHG emissions by 2050, compared to the reference scenario in the same year. This equates to a 74 % reduction of energy-related industrial greenhouse gas emissions until 2050, compared to 1990. Simultaneously electricity consumption increases by 25 % and fossil FEC decreases by 37 % by 2050. Total FEC is 78 TWh (13 %) lower in the electrification scenario compared to the reference case, which

[14] For the effect on process related emissions cf. [18].

mainly results from the efficiency gains realized by using industrial heat pumps for process heat below 100 °C and H&HW. The displacement of gas results from low temperature electrification and the substitution of gas fired flat and container glass furnaces through electrical glass furnaces. The reduction of coal, which includes coke, occurs mainly due to the process substitution for the primary steel production. Furthermore, the diagram shows that electrification commences in 2021 and is completed by 2040, as electricity consumption does not increase between 2040 and 2050.[15] Between 2040 and 2050 a slight reduction of the electrical FEC occurs due to a marginal decrease in industrial production.

Due to a further reduction of the emission coefficient of power generation emissions from electricity consumption are reduced between 2040 and 2050, although the electricity consumption in the industry sector remains constant. Figure 6 shows the energy related $CO_2$-emissions and the $CO_2$-coefficient of power generation for both scenarios.

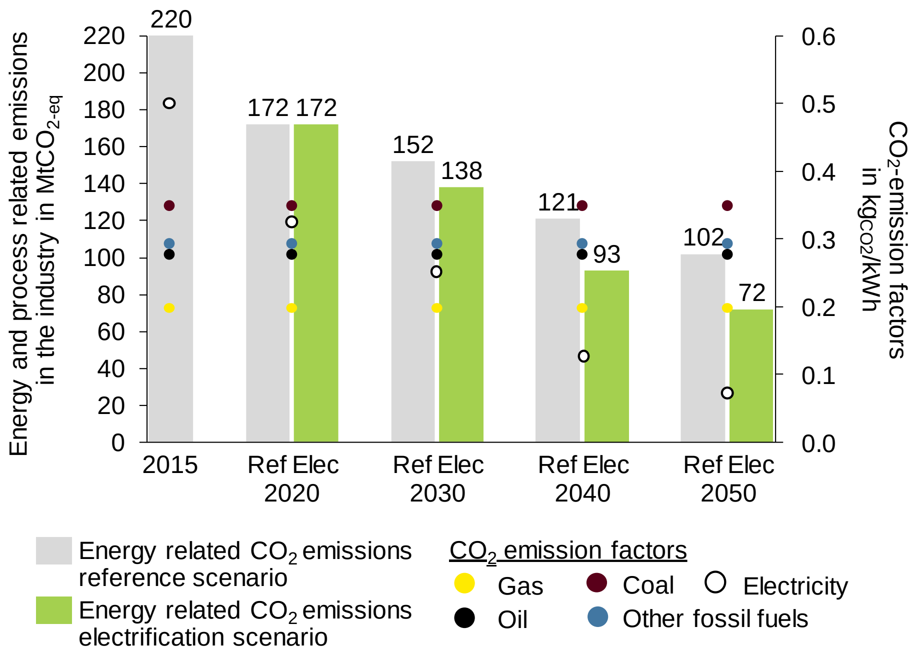


*Figure 6: Energy related $CO_2$-emissions in the industry for the reference and electrification scenario in $MtCO_2$ and $CO_2$-coefficient of power generation in $kg_{CO2}$/kWh (2015 – 2050)*

The $CO_2$-emission coefficient for power generation used to derive the resulting energy related $CO_2$-emissions through electricity consumption results from a model iteration with the energy system model ISAaR (cf. section 2). Hereby the load curves from the reference scenario for all energy end-use sectors and the expansion of renewable energy sources for electricity production according to [32] (scenario B) serve as the basis for calculating the power plant dispatch and resulting hourly emission factors. The results in Figure 6 show that additional $CO_2$ emission reduction is achieved in the electrification scenario compared to the reference scenario. This in turn results from both the efficiency gains due to electrification and the relative improvement of the $CO_2$ coefficient of power generation compared to the $CO_2$-coefficient of the displaced fossil energy carriers gas, coal, oil and other fuels (cf. Figure 6).

[15] Technical lifetimes are the basis for the transition speed.

The effect of electrification on the FEC in each industry branch is shown in Figure 7. Reductions in FEC through electrification compared to the reference case are noticeable in the low-temperature industry branches *Food and tobacco* and *Paper*. In these processes a variety of heat transfer processes (e.g. thermal drying of paper, steam drying of sugar beet pulp, pasteurization of milk) result in a high demand for process heat below 240 °C, which is electrified using heat pumps and electrode boilers [33], [17], [9], [12]. Furthermore, process substitutions in the steel and glass industry result in a reduction of the process specific FEC of 19 % and 14 % by 2050, with respect to the reference scenario.

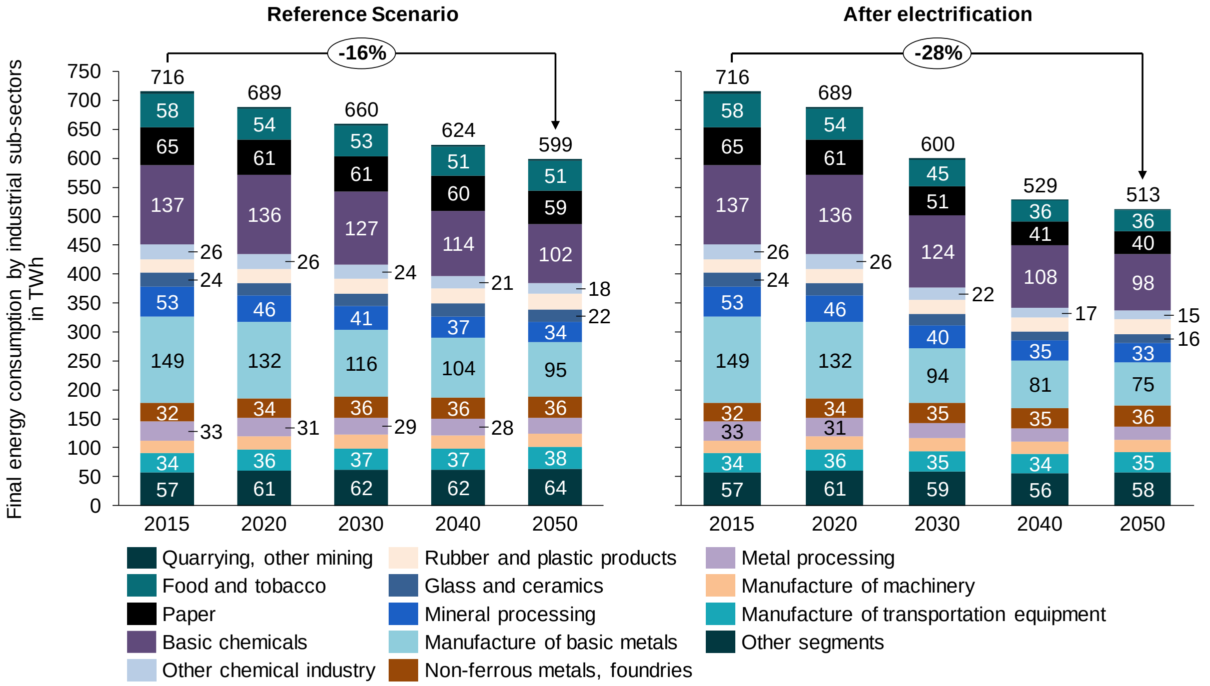


*Figure 7: Final energy consumption by industry sub-sector for the reference and electrification scenario in TWh (2015 – 2050)*

The left-hand side of Figure 8 shows the substitution of primary steel through secondary steel. Hereby the scrap availability poses a barrier to full electrification [33]. Recently published energy system scenarios assume ratios of primary to secondary steel making by 2050 in a range from approximately 1:1 [22] to 1:2 [34]. The assumption made for this calculation is consequently in line with the concept of the *low-hanging fruits* electrification scenario, which assumes high exchange rates in the areas relevant for electrification.

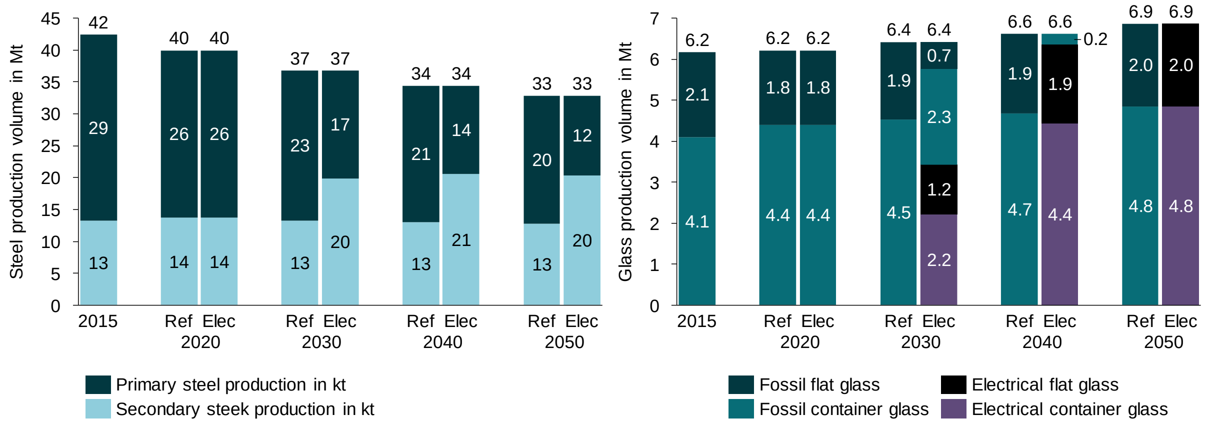


*Figure 8: Production volume for primary and secondary steel making and fossil and electrical flat and container glass in Mt for the reference and electrification scenario (2015 - 2050)*

It is assumed that there is no technical barrier to the full electrification of container and flat glass until 2050 [38]. Current barriers such as the limited daily production tonnage of electrical furnaces, their restricted lifetimes and comparably high costs are not considered barriers to electrification in the long run [24], [38]. The implemented transition rate and the assumed increase in total production volume of container and flat glass results in the electrification of 84 % of the glass production volume by 2050 [26].

## 5 Discussion and Conclusion

The complex and heterogeneous nature of the industry sector results in a variety of challenges when attempting to model its structure and the effect of GHG abatement measures on industrial final energy consumption.

In order to quantify the status quo of the industry sector and the effect of different abatement measures SmInd taps on a wide range of literature values, statistical figures and primary data. In SmInd, primary data from energy audits [35] is used to derive abatement potentials for cross-sectional technologies and sub-sector load curves. Using primary data as opposed to literature values allows for the gradual expansion and therefore successive improvement of the database. As acknowledged by other publications literature data focusing on the energy consumption of industrial processes or the quantification of GHG abatement measures, is sometimes incomplete, outdated or flawed [8]. The literature data used for the calculations in this paper was consequently validated in an iterative procedure according to [5]. For statistical data such as the sub-sectoral final energy consumption, only widely acknowledged sources such as the *Federal Statistcal Office* were considered.

The heterogeneity of industrial processes poses a barrier to the full bottom-up coverage of the sector. This results in the challenge that both top-down and bottom-up data need to be combined within an industry model, which aims to model the entire sector as well as individual processes. In SmInd, the energy application matrix is used to model changes in the bottom-up process and top-down statistical energy consumption. The energy application matrix shows the share of energy carriers by application in each industry sub-sector. A variety of ideas for further research can be connected to the structure of the energy application matrix. Firstly, SmInd scenarios (including the scenario discussed in this publication) can be expanded to include further European countries by implementing different energy application matrices.

Secondly, the granularity of the applications modeled in the $\boldsymbol{EAM}$ can be adapted to include different temperature levels, allowing for a further refinement of electrification scenario results. In this context the implementation of different temperature statistics such as [9], [10], [11] and [12] should be analyzed, as these can have a significant influence on the realized electrification potentials.

With respect to the implementation of GHG abatement measures SmInd uses a modular setup. Hereby, three dimensions are presented in this paper: measure type, measure cluster and the degree of bottom-up industry sector coverage. The modular structure of SmInd allows for the gradual addition of measure types and clusters. This results in a wide range of possibilities for further research, including but not limited to the modelling of non-energy related emissions [2], excess heat potentials and feed-stock flows.

Electrification as performed in the low-hanging fruits electrification scenario occurs in areas in which it is technically possible and likely to occur in the future. However, the transformation speed presented in this paper should be interpreted as an upper-bound estimate. The results show that almost the full electrification of the considered processes occurs before 2050. This results from the fact that the measure implementation speed is bound to the technical lifetime of the existing fossil-fueled infrastructure. In most cases, the technical lifetime of industrial equipment can be prolonged significantly through retrofit measures. Moreover, the scenario results do not consider further barriers to electrification (e.g. economical or company specific barriers). It is consequently likely that a full implementation cycle is considerably longer than presented in this analysis.

## 6 Bibliography


[1] Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung. Berlin: Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMU), 2016

[2] Pichlmaier, Simon et al.: Development of Application-Related Emissions in the Course of the German Energy Transition. In: IEWT 2019 11. Internationale Energiewirtschaftstagung. Wien: TU Wien, 2019.

[3] Bhattacharyya, Subhes: Energy Economics - Concepts, Issues, Markets and Governance. London: Springer, 2011

[4] Klassifikationen - Gliederung der Klassifikation der Wirtschaftszweige, Ausgabe 2008 (WZ 2008). Wiesbaden: Statistische Bundesamt, 2008

[5] Guminski, Andrej et al.: Energiewende in der Industrie: Methodik zur Identifikation und Quantifizierung von Dekarbonisierungsmaßnahmen. In: et Energiewirtschaftliche Tagesfragen (Ausgabe 12/2017). Essen: etv Energieverlag GmbH, 2017.

[6] Rohde, Clemens: Erstellung von Anwendungsbilanzen für die Jahre 2013 bis 2015 mit Aktualisierung der Anwendungsbilanzen der Jahre 2009 bis 2012. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung (ISI), 2016

[7] Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2016 - Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990 - 2014. Dessau-Roßlau: Umweltbundesamt (UBA), 2016

[8] Fleiter, Tobias et al.: A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. In: Energy Strategy Reviews 22 (2018) 237-254. Philadelphia, USA: Elsevier, 2018.

[9] Unger, H.; Wagner, H.-J.; et al.: Validierung und kommunale Disaggregierung des Expertensystems HERAKLES - Abschlussbericht zum Vorhaben 258 114 98. Bochum: Lehrstuhl für Energiesysteme und Energiewirtschaft, Ruhr-Universität Bochum (LEE), 2002

[10] Sander, Kai et al.: Analyse der industriellen Nutzenergienachfrage nach Sektoren und Betriebsgrößenklassen - Projektbericht. Stuttgart: Institut für Energiewirtschaft und Rationelle Energieanwendung IER, 2002.

[11] Blesl, Markus; Kessler, Alois: Energieeffizienz in der Industrie in: Springer Verlag. Berlin Heidelberg: Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), Universität Stuttgart, EnBW Energie Baden-Württemberg AG, Forschung und Innovation, Karlsruhe, 2013.

[12] Blesl, Markus et al.: Energieeffizienz in der Industrie - 2. Auflage. Stuttgart, Karlsruhe: Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), Universtität Stuttgart, 2017.

[13] BMWi: Energiedaten: Gesamtausgabe. Berlin: BMWi, 2018.

[14] Bühler, Fabian et al.: Evaluation of energy saving potentials, costs and uncertainties in the chemical industry in Germany. In: Applied Energy Volume 228. Philadelphia, USA: Elsevier, 2018.

[15] Unverbindliche Preisempfehlung - Lampen. Garching: LEDVANCE GmbH, 2017.

[16] Produzierendes Gewerbe - Stromerzeugungsanlagen der Betriebe im Verarbeitenden Gewerbe sowie im Bergbau und in der Gewinnung von Steinen und Erden 2015 in: Fachserie 4 Reihe 6.4. Wiesbaden: Statistisches Bundesamt (destatis), 2016

[17] Brunke, Jean-Christian: Energieeinsparpotenziale von energieintensiven Produktionsprozessen in Deutschland - Eine Analyse mit Hilfe von Energieeinsparkostenkurven. Dissertation. Herausgegeben durch die Universität Stuttgart - Institut für Energiewirtschaft und Rationelle Energieanwendung, geprüft von Voß, Alfred und Sauer, Alexander: Stuttgart, 2016.

[18] Hübner, Tobias et al.: Modellgestützte Analyse synthetischer Brennstoffe in der Industrie bei ambitioniertem Klimaschutz. München: Forschungsgesellschaft für Energiewirtschaft (FfE), 2019.

[19] Gobmaier, Thomas Dr.-Ing.; Eberl, Benedikt; von Roon, Serafin Dr.-Ing.: Studie über Einflussfaktoren auf den zukünftigen Leistungsbedarf der Verteilnetzbetreiber. München: Forschungsgesellschaft für Energiewirtschaft mbH, 2014 – ISBN: 978-3-945029-97-8; ISBN-A: 10.978.3945029/978

[20] Pezzutto, Simon et al.: Hotmaps - D2.3 WP2 Report – Open Data Set for the EU28. Wien, Österreich: Technische Universität Wien (TU Wien), Institute of Energy Systems and Electrical Drives, Energy Economics Group (EEG), 2018.

[21] Destatis: Produktionsindex. In: https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/IndustrieVerarbeitendesGewerbe/Methoden/Produktionsindex.html. (Abruf am 2018-05-01); (Archived by WebCite® at http://www.webcitation.org/6z5gzjrdy); Wiesbaden: Destatis, Statistisches Bundesamt, 2018.

[22] Gebert, Philipp et al.: Klimapfade für Deutschland. München: The Boston Consulting Group (BCG), prognos, 2018.

[23] The FfE Regionalized Energy System Model (FREM). Munich: Forschungsstelle für Energiewirtschaft e.V. (FfE), 2014

[24] Guminski, Andrej; von Roon, Serafin: Transition Towards an “All-electric World” - Developing a Merit-Order of Electrification for the German Energy System in: 10. Internationale Energiewirtschaftstagung an der TU Wien. Wien, Österreich: Technische Universität Wien, 2017

[25] Schlesinger, Michael; Lindenberger, Dietmar; Lutz, Christian: Entwicklung der Energiemärkte - Energiereferenzprognose - Projekt Nr. 57/12 - Studie im Auftrag des Bundesministeriums für Wirtschaft und Technologie . Berlin: Bundesministerium für Wirtschaft und Technologie (BMWi), 2014.

[26] Wohlfahrt, Katharina; Schlomann, Barbara; Jochem, Eberhard; Reitze, Felix; Schön, Michael; Toro, Felipe: Sektorale Emissionspfade in Deutschland bis 2050 - Sektoren Gewerbe, Handel, Dienstleistungen (GHD) und Industrie. Karlsruhe: Öko-Institut e.V., 2016

[27] Lechtenböhmer, Stefan et al.: Decarbonising the energy intensive basic materials industry through electrification e Implications for future EU electricity demand. In: Energy 2016, 1-9. Amsterdam: Elsevier, 2016.

[28] Gruber, Anna; Biedermann, Franziska; von Roon, Serafin: Industrielles Power-to-Heat Potenzial in: Vortrag bei der IEWT 2015 in Wien. München: Forschungsgesellschaft für Energiewirtschaft mbH, 2015

[29] Gerhardt, Norman et al.: Potenziale für Strom im Wärmemarkt bis 2050 - Wärmeversorgung in flexiblen Energieversorgungssystemen mit hohen Anteilen an erneuerbaren Energien. Frankfurt am Main: VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V., 2015

[30] Otto, Alexander; Robinius, Martin; Grube, Thomas; Schiebahn, Sebastian; Praktiknjo, Aaron; Stolten, Detlef: Power-to-Steel - Reducing CO2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry in: Energies (4), 2017, S. 451. Basel: MDPI, 2017

[31] Echterhof, Thomas: Interview - Electrification of metal production and processing. München: FfE GmbH, 2015

[32] Szenariorahmen für den Netzentwicklungsplan Strom 2030 (Version 2019) - Entwurf der Übertragungsnetzbetreiber. Berlin, Dortmund, Bayreuth, Stuttgart: 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, 2018.

[33] Fleiter, Tobias; Schlomann, Barbara; Eichhammer, Wolfgang: Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien - Einsparpotentiale, Hemmnisse und Instrumente in: ISI Schriftenreihe "Innovationspotentiale". Stuttgart: Fraunhofer-Institut für Systemtechnik und Innovationsforschung (Fraunhofer ISI), 2013

[34] Günther, Jens et al.: Den Weg zu einem treibhausgasneutralen Deutschland ressourcenschonend gestalten. Berlin: Umweltbundesamt, 2017.

[35] Lernende Energieeffizienz-Netzwerke (LEEN): München-Oberbayern, Südbayern, Vorarlberg I und II, Chiemgau-Rupertiwinkel, Bayerngas, Verbund - laufende Projekte. München: Forschungsgesellschaft für Energiewirtschaft mbH, 2014

[36] Böing, Felix; Murmann, Alexander; Pellinger, Dr. Christoph; Bruckmeier, Andreas; Kern, Timo; Mongin, Thibaud: Assessment of grid optimising measures for the German transmission grid using open source grid data in: Journal of Physics: Conference Series. Oldenburg: IOP Publishing, 2018

[37] Kern, Timo et al.: Modellierung des europäischen Gasmarkts zur Darstellung verschiedener Gasimportszenarien. In: 10 . Internationale Energiewirtschaftstagung, IEWT; Wien: FfE GmbH, 2017.

[38] Veitengruber, Frank et al.: Potenzialanalyse zur Hybridisierung von Prozessen in der Grundstoffindustrie. München: Forschungsgesellschaft für Energiewirtschaft mbH, 2019.