Electrification decarbonization efficiency in Europe – a case study for the industry sector

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Abstract

Numerous national goal based energy system scenarios from a variety of countries assume the electrification of industrial process heat, on the path towards deep decarbonization until 2050. In this context, the evaluation of industrial process heat measures with respect to cost, additional electrical final energy consumption and the position of industrial loads becomes increasingly important. In this paper, industrial low temperature electrification measures (< 200 °C) for Germany and 15 neighboring states are evaluated with respect to these aspects. Across all electrification measures emissions are reduced by 55 % (Poland) to 99 % (Norway). Total absolute annualized electrification costs from an investor cost perspective in 2050, range from -0.7 bn € (Sweden) to 8.4 bn € (Germany). Abatement costs for individual electrification measures lie between -1300 €/t_{CO2} (Italy) to 8200 (Czech Republic). These extreme values occur in areas in which very low emission differences are achieved through electrification. This calls for caution with respect to the interpretation of extreme abatement cost values. Furthermore, a new measure for the system efficiency of electrification measures is introduced. The "electrification decarbonization efficiency" measures the additional electrical final energy consumption per ton of avoided CO_2. The range of median values for the decarbonization efficiency across all electrification measures and countries lies between 1 and 5 MWh/t_{CO2}.

Keywords: electrification, European energy transition, industry sector, process heat, industrial processes, sectorcoupling

1 Introduction - decarbonization through electrification

In a variety of German energy system studies, the substitution of fossil fuels through electricity on the energy demand-side (electrification) has been displayed as a key deep decarbonization measure. In addition, possible system interdependencies have been analyzed on a national level [1]. Such national analyses however do not consider possible changes in the energy system composition that could occur due to decarbonization through electrification in neighboring countries. Neglecting these developments could lead to false conclusions about the resulting system effects in a European context, especially if extreme electrification rates are assumed. In order to assess the effects of the simultaneous increase in electricity demand in several European countries, an overview of the costs and potentials of electrification in these countries is required. Another key factor is the position of possible additional electrical loads. In this context, especially large industrial loads are relevant. It is the aim of this paper to provide an overview of the electrification costs and potentials for Germany and its electrical neighboring countries[1]. Furthermore, a regionalized European "low-hanging fruits" electrification scenario is determined for the industry sector in NUTS-3 resolution. Results are presented for the years 2015 and 2050.

2 Evaluating electrification measures – methodology and assumptions

Figure 1 shows the three-step methodology used to derive electrification costs and potentials as well as the regionalization of industrial loads. In this section, the methodology, input data and assumptions for each step are explained.

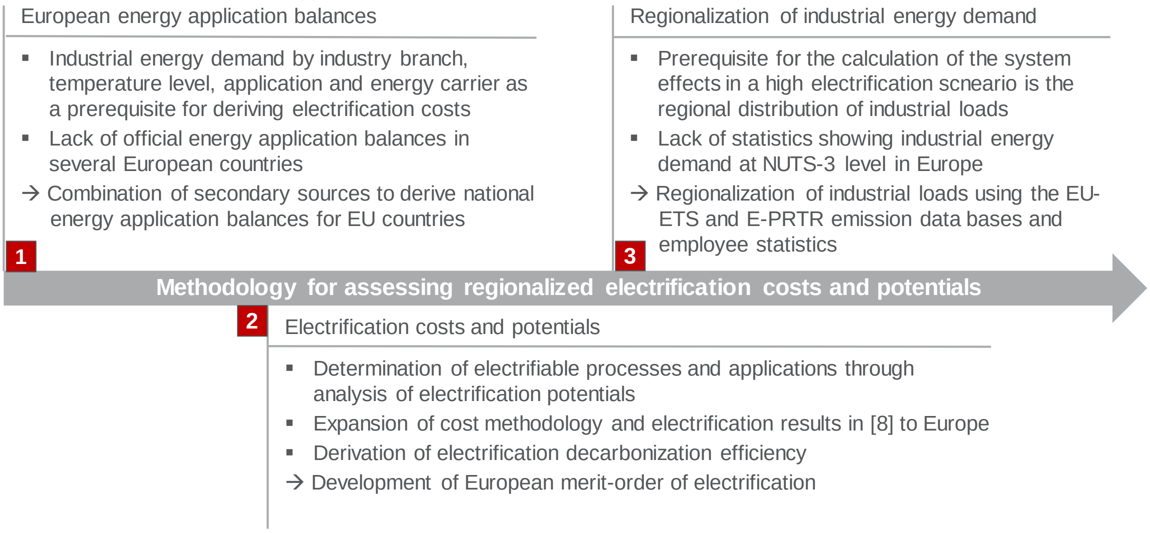

Figure 1: Methodological steps towards deriving regionalized electrification potentials and costs

2.1 European energy application balances and electrification potential

In a first step, the theoretical electrification potential (tep) is determined for Germany and its electrical neighbors. The implemented methodology combines two approaches: First, the final energy consumption (fec) of the countries (cr) in scope of the analysis is structured according to energy carriers (ec), industry branches (ib) and applications (ap). This step is performed based on the energy statistics published in [2], [3], [4], [5], [6] and [7]. Secondly, the electrical (el) and renewable (res) final energy consumption is subtracted from the total FEC to give the TEP for a certain year, y, as defined in [8]. The theoretical industrial electrification potential ($tep_{cr,ind}$) per country is calculated using expression (2-1).

$$tep_{cr,ind} = fec_{tot,cr,ind,y} - fec_{elec,cr,ind,y} - fec_{res,cr,ind,y}$$
$$cr \in DE, SE, NO, DK, GB, FR, BE, NL, IT, CH, SL, HU, PL, CZ, SK, AT \qquad (2\text{-}1)$$

Energy application balances build the basis for the development of demand-side scenarios and are consequently the starting point for deriving the TEP. For Germany, reliable statistical data exists, which shows the FEC by industry branch, energy carrier, application and sector

1 Sweden, Norway, Denmark, UK (interconnection planned and operable by 2023 [46]), France, Belgium, Netherlands, Italy, Switzerland, Slovenia, Hungary, Poland, Czech Republic, Slovakia, Austria.

[3]. An overview of national energy-application balances for EU countries provided in [4] shows that, excluding Germany, five of the analyzed 15 countries provide more detailed national energy application balances for the industry sector (Austria, France, Switzerland, United Kingdom, Italy). To achieve a consistent starting point for the development of demand-side electrification scenarios, national energy application balances are derived using a homogeneous data set. For each country and industry branch the share of energy consumption by energy carrier and application is summarized in an energy application matrix ($\boldsymbol{EAM}$) [9], [10], [3], [4], [5], [6], [7]. The latter is then multiplied by the final energy consumption for each energy carrier in the respective industry branch [2]. Through this stepwise procedure, a quick upgrade of the national energy application balances is possible, as soon as new data is published. Expression (2-2) shows the energy application matrix that is constructed based on the procedure shown in Figure 2.

$$\boldsymbol{EAM}_{cr,ib} = \begin{pmatrix} eam_{1,1} & \cdots & eam_{1,ap} \\ \vdots & \ddots & \vdots \\ eam_{ec,1} & \cdots & eam_{ec,ap} \end{pmatrix}_{cr,ib} \tag{2-2}$$

Steps one to three in Figure 2 are performed for each country and industry branch. This procedure is a result of the type and style of available data, required to derive national energy application matrices.

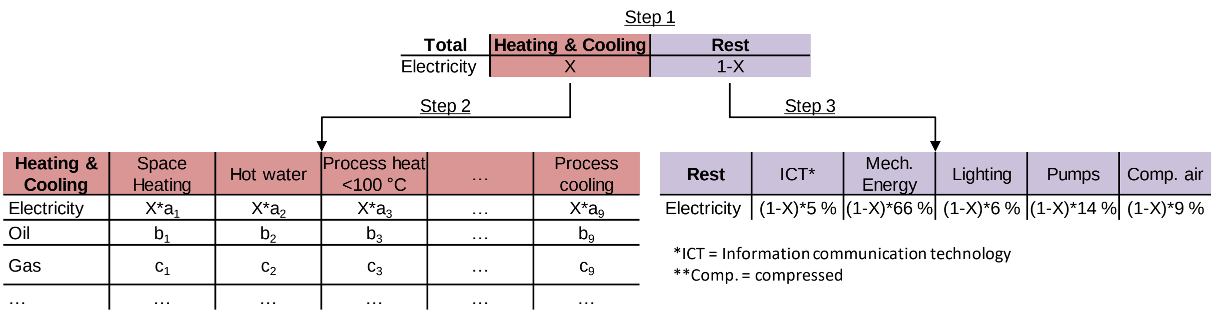

Figure 2: Stepwise procedure used to derive national energy application matrices for the industry sector

In **step 1**, the share (X) of heating and cooling (H&C) applications of total electrical final energy consumption ($fec_{cr,ib,el}$) in each industry branch is derived from [11]. The shares are calculated based on data from 2012. To date, updates of these shares are not possible because an update of [11] has not been published. The remaining share of electrical FEC ($1 - X$) is allocated to non-H&C applications. [11] assumes that the latter are solely powered by electricity. In **step 2**, H&C applications are split into *space heating*, *process heat*, *climate cold*, *warm water* and *process cooling* using [7]. Hereby the heat generated by heat pumps is allocated to the energy carrier electricity using a coefficient of performance of three [5]. The base year for this calculation is 2012. Non-H&C applications are not differentiated in [7] and [11]. Hence, in **step 3**, detailed German energy application balances [3] are used to split the non-heating and cooling energy consumption share into *information communication technology (ICT)*, *mechanical energy* and *lighting, pumps* and *compressed air*. The base year for step 3 is 2014. Annual updates of these shares are possible. The share of ICT, mechanical energy, lighting, pumps and compressed air are set to 5 %, 66 %, 6 %, 14 % and 9 % respectively. These shares are assumed for all countries and industry branches. The resulting energy application matrix is further processed by scaling each row with the final energy consumption of the respective energy carrier for a given country, year and industry branch. This builds the basis for calculating the theoretical industrial electrification potential according to expression (2-1). The total final energy consumption in 2014 and theoretical electrification potential for Germany and its electrical neighbors is shown in Figure 3.

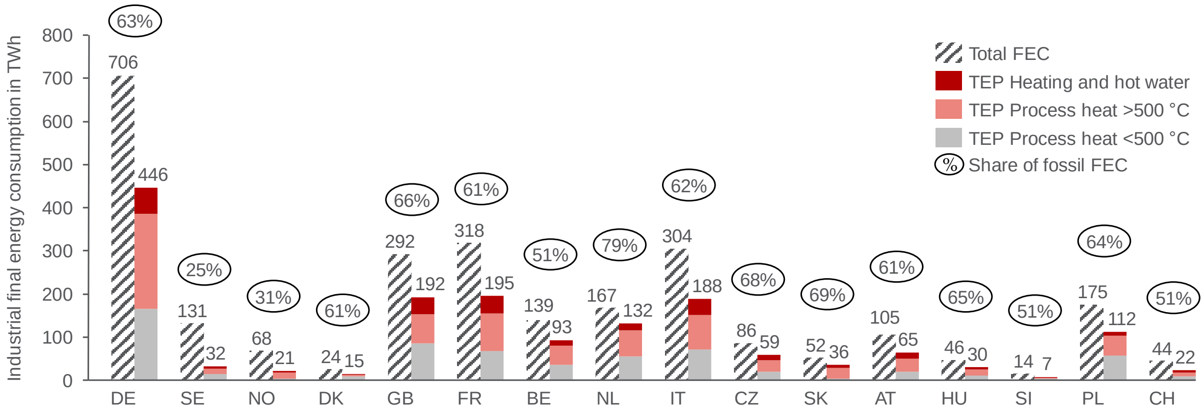

Figure 3: Total industrial final energy consumption and theoretical electrification potential for Germany and electrical neighbors in TWh (2014)[2]

Due to the assumption that all non-H&C applications run on electricity, the remaining and theoretically electrifiable industrial applications are heating and hot water as well as process heat (cf. Figure 3). The figure shows that the share of renewable and electrical energy consumption of total FEC varies between 21 % in the Netherlands and 75 % in Sweden. This share is a result of the historical energy system development in each country.

In Sweden for instance, a high share of nuclear and hydro power in electricity generation (41 % and 42 % in 2014, respectively) leads to a comparably low CO_2-coefficient of power production of 8 g/kWh (Germany 2014: 532 g/kWh) [12], [13]. This also results in lower electricity prices in Sweden compared to Germany for both residential and industrial consumers[3] [13], resulting in a higher share of electricity consumption of total FEC in Sweden (35 %) compared to Germany (22 %). The low electrification potential in Sweden's industry sector however results from the high share of biomass used in Sweden's largest industry branch: Paper, pulp and print. 35 % of total industrial FEC are consumed in the Paper, pulp and print industry, of which 95 % are biomass. Approximately half of Sweden's land area is covered by forests [14], resulting in a high biomass availability and low prices.

2.2 Electrification costs and decarbonization efficiency

The electrification potential shown in Figure 3 poses the starting point for deriving electrification costs as well as the electrification decarbonization efficiency. In this section, the methodology used in [8] is expanded to include the countries in scope of the analysis as well as the emissions resulting from electrification measures.

Electrification cost methodology

2 Fossil FEC for cooling applications is negligible (< 1 % of total fossil FEC in each country) and therefore not depicted in the figure. The TEP varies based on the year. Heating and hot water consumption has not been adjusted for temperature differences.
3 Households (2014): 30 ct/kWh Germany vs. 19 ct/kWh Sweden. Industrial consumers with an annual consumption between 2 GWh to 20 GWh (2014): 18 ct/kWh Germany and 8 ct/kWh Sweden.

The electrification cost methodology is based on the *relevant costing* approach described in [15]. Relevant costing is a *total cost* approach which includes only those cost components which differ between two alternatives. In this case the electrical alternative technology is compared to a fossil reference technology. The annualized differential cost of electrification in a country, for a certain application and year ($adc_{cr,ap,y}$) is calculated by expression (2-3).

$$adc_{cr,ap,y} = \frac{\sum_{r=1}^{n}\left(a_{OPEX,r,cr,ap,y}^{elec} - a_{OPEX,r,cr,ap,y}^{ref}\right) + \sum_{r=1}^{n}\left(a_{CAPEX,r,cr,ap,y}^{elec} - a_{CAPEX,r,cr,ap,y}^{ref}\right)}{fec_{ref,cr,ap,y}} \tag{2-3}$$

fec	$= final\ energy\ consumption$	elec	$= electrical\ system$	ref	$=reference\ system$
$CAPEX$	$=Capital\ expenditure$	r	$=relevant\ costs$	cr	$= country$
$OPEX$	$=Operating\ expenditure$	ap	$= application$	y	$= year$
n	$=no.of\ relevant\ cost\ sets$				

In the numerator of expression (2-3) the absolute annualized differential cost of electrification is calculated ($aDC_{cr,ap,y}$). To do so, the annualized difference for operating expenditure ($a_{OPEX,r,cr,ap,y}^{elec,ref}$) between the electrical and reference system is added to the annualized difference for all relevant capital expenditure ($a_{CAPEX,r,cr,ap,y}^{elec,ref}$). The denominator is the amount of fossil FEC that is displaced through the electrification procedure. Electrification costs are consequently interpreted as specific additional or avoided costs resulting from the substitution of fossil through electrical appliances [8]. All $OPEX$ are treated as real annual costs and are therefore not discounted [8]. All $CAPEX$ are annualized using expression (2-4).

$$a_{CAPEX,r,cr,ap,y}^{elec,ref} = I_0^{elec,ref} * \frac{i * (1+i)^t}{(1+i)^t - 1}; i \in sys, inv \tag{2-4}$$

I_0	$= Technology\ investment$	i	= discount rate	t	= technology lifetime

Expression (2-3) can be adapted to give the marginal CO_2 abatement costs of electrification measures by expanding the denominator to give the emission difference between fossil reference technology and electrical alternative (cf. (2-5)).

$$mc_{cr,ap,y} = \frac{aDC_{cr,ap,y}}{\Delta fec_{cr,ap,y} * emf_{ref,cr,y} - fec_{elec,cr,ap,y} * emf_{elec,cr,y}} \tag{2-5}$$

Hereby, the emission factors of the displaced fossil, $emf_{ref,cr,y}$, and additional electrical FEC, $emf_{elec,cr,y}$, are used to derive the emission difference resulting from electrification. The displaced fossil final energy consumption, $\Delta fec_{cr,ap,y}$, and the additional electrical final energy consumption, $fec_{elec,cr,ap,y}$, are calculated based on technology related assumptions. Hereby the following steps are performed [8]:

1. Calculation of thermal energy demand per application: starting point is the current final energy consumption, to which the utilization rate of the currently installed heating system is applied
2. Determination of installed thermal power per application for reference and electrical technology (used to calculate CAPEX): key assumptions are full load hours for each industry branch and a 50 % security margin which is added to the calculated system size [16].

3. Calculation of reference fossil final energy consumption[4]
4. Derivation of electrical final energy consumption based on thermal energy demand: this is based on the utilization rate of the electrical heating system.

The level of granularity at which these steps are performed can vary depending on the research question at hand and the data availability in the industry sector.

Electrification cost perspective

While the electrification cost methodology shows how electrification costs are calculated, the cost perspective defines how these costs can be interpreted. The selected costing approach assumes the investor cost perspective. The relevant cost components differ according to the perspective. The investor perspective includes all cost components, which are visible to a company implementing the electrical end-use application. Relevant operating expenditure elements therefore include energy carrier prices including all taxes, levies and surcharges, emission certificate prices, other operation and maintenance costs. In terms of CAPEX, the investor discount rate reflects the investor's opportunity cost and thereby the profit expectations of the company at hand [17], [18].

Electrification decarbonization efficiency

In a variety of energy system scenarios such as [19], [20] or [21] electrification has been considered as a key defossilization strategy. However, it has also been pointed out that high electrification rates result in increased stress for the energy system, as transmission capacities are utilized to their limit and additional variable renewable energy capacities are required to provide emission free electricity [1]. From a technical system perspective, it is consequently advisable to pursue electrification measures which reduce emissions, but also to minimize the additional electricity consumption. In order to analyze this effect for a broad set of electrification options a new measure termed "electrification decarbonization efficiency" is introduced. It is summarized in expression (2-6) and shows the additional electrical FEC ($fec_{elec,cr,ap,y}$) per mitigated ton of CO_2 ($\Delta E_{cr,ap,y}$).

$$Deff_{cr,ap,y} = \frac{fec_{elec,cr,ap,y}}{\Delta E_{cr,ap,y}} \tag{2-6}$$

Electrification and reference scenario assumptions

In this analysis, the reference scenario of the project Dynamis [22] is used as a basis for calculating electrification costs until 2050 [23]. The scenario describes a full energy system development from 2020 to 2050. The development of the load in each energy end-use sector is based on [24]. The scenario can be characterized as a transition pathway with low amounts of electrification and synthetic fuels but a high share of energy efficiency measures. The supply-side reaction to the load development is simulated using the linear optimization model

4 This is the FEC that would occur if the currently installed system would be exchanged with a new fossil fueled system. The currently installed system and the reference system can differ.

ISAaR [25]. The resulting time-dependent emission factors for electricity as well as energy and emission certificate prices are used as a basis for calculating electrification costs. System repercussions resulting from increased electrification are not considered.

Emission certificate prices are based on exogenous model assumptions [23]. It is assumed, that only energy intensive industry branches are required to purchase emission certificates (cf. Table 1). Emission factor development, emission certificate and energy prices are provided in the appendix.

Table 1: Categorization of industry branches according to energy intensity [26]

Energy intensive industrial branches	Iron & steel industry, Chemical & Petrochemical industry, Non-ferrous metal industry, Non-metallic Minerals, Paper, Pulp and Print
Other industrial branches	Transport Equipment, Machinery, Mining and Quarrying, Food and Tobacco, Wood and Wood Products, Construction, Textile and Leather, Non-specified (Industry)

Energy carrier prices are mainly based on [13].[5] It is assumed that taxes, levies and surcharges remain at the 2015 level until 2050. Energy procurement costs are a result of the simulation [23]. Energy carrier prices are differentiated according to the industry branch (cf. Table 4 in the appendix). Hereby the average annual energy consumption of the industry branch is used as a decision criteria [13]. Further details concerning the energy carrier price assumptions are summarized in the appendix (Table 6).

Building on the reference scenario results a “low-hanging fruits” electrification scenario is constructed. In this scenario, electrification is confined to low-temperature process heat below 200 °C and heating and hot water. Hereby, it is assumed that heating and hot water have a joint source. Process heat is further differentiated according to temperature levels. For heating and hot water as well as process heat below 100 °C an industrial ground source heat pump is used as the electrical end-use technology. Between 100 °C and 200 °C an electrode boiler is assumed. The assumed reference technologies are temperature level, energy carrier and application specific, but independent of country, year and industry branch.[6] The full set of technologies including technical parameters is listed in the appendix (Table 3).

Technology costs are considered constant over time and do not vary between countries. This is justifiable as the share of CAPEX of total annualized electrification cost is in the range of single digit percentages [8]. Technology costs are summarized in the appendix (Table 3).

In the “low-hanging fruits” electrification scenario full-electrification is assumed until 2050. In terms of the areas in which electrification is allowed, the scenario is consequently conservative. The transition rates assumed in the electrifiable areas are however extreme. Hereby the

5 For Sweden and Norway a wide range of assumptions were made to derive energy carrier prices for coal, gas and electricity. These countries are not covered by the Eurostat data set, which is used as a basis for deriving energy carrier prices in the different industry sectors.

6 It is assumed that the source of hot water and steam used in the analyzed applications is independent of the process itself and therefore a differentiation according to industry branches not required [47].

underlying assumption is that fossil equipment is phased out of the system as soon as it reaches its end-of-life [8].

2.3 Regionalization of industrial energy demand

To provide the basis for evaluating the effects of electrification on the energy system, the "low-hanging fruits" electrification scenario results are regionalized in NUTS-3 resolution. Basis for the regionalization of industrial final energy consumption are the European emission trading system (EU-ETS) [27], the European pollutant transfer registry databases (E-PRTR) [28], several additional industry branch specific databases as well as employee [29] and population data [30], [31]. Figure 4 provides an overview of the regionalization methodology.

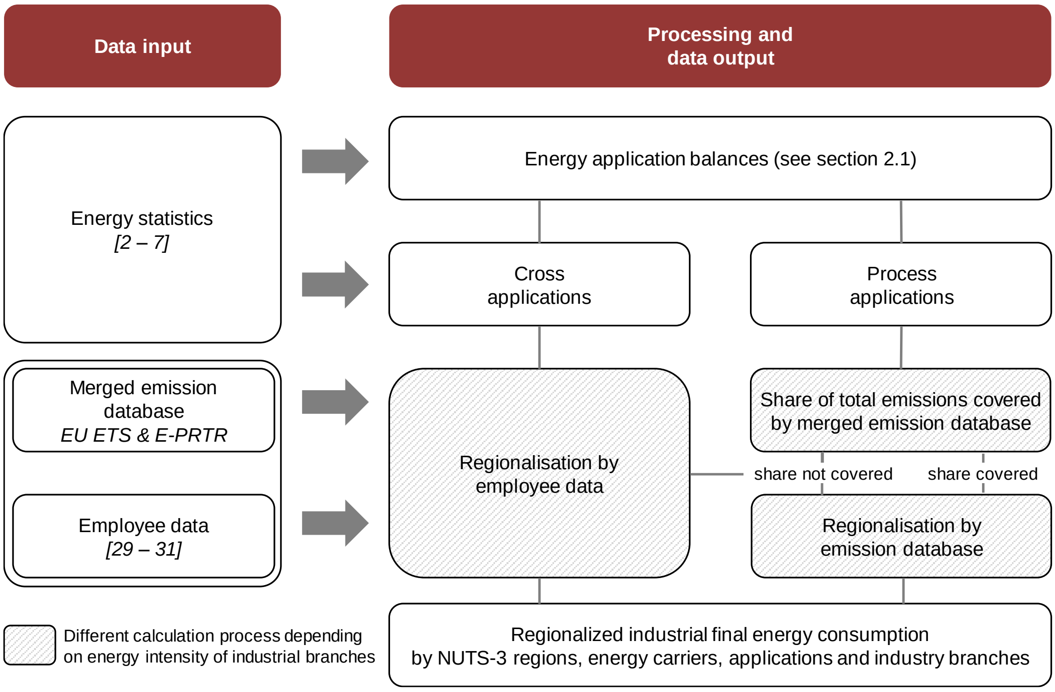

Figure 4: Regionalization methodology overview for FEC in the industry sector[7]

The figure shows, that the country, industry branch, energy carrier and application specific energy consumption calculated in the energy application balances is distributed to NUTS-3 regions using an allocation key. The type of key used, thereby depends on the energy intensity of the industry branch (Table 1) as well as the application (Table 2).

Table 2: Classification of applications for regionalization of FEC in the industry sector

Process applications	Electrical drives (electricity), Electrical pumps (electricity), Other mechanical energy (electricity), Process heat (electricity), Process cold (electricity), Mechanical energy (fossil fuels & renew.), Process heat (fossil fuels & renew.)
Cross applications	Space heating (all energy carriers), Warm water (all energy carriers), Space cooling (electricity), ICT (electricity), Lighting (electricity)

7 For the case of Switzerland regionalization occurs based on employee numbers, which are available at NUTS-3 resolution [48].

Energy intensive industries and process applications: Basis for regionalizing the energy consumption of process applications in energy intensive industries are industry site specific emissions derived from the EU-ETS and E-PRTR emission databases. The latter are combined using a matching algorithm. The resulting merged database lists 5076 industry installations, with 741 uniquely listed in the E-PRTR, 3,768 uniquely listed in the EU-ETS and 567 listed in both databases. In order to validate and complement this list of industry installations, the production sites of the energy intensive industrial processes cement [32], lime [33], chlorine [34], glass [35] and steel [36] were determined through other sources and compared to the merged database. The list was then adapted based on the result of the comparison.[8] The energy consumed by process applications in energy intensive industry branches is consequently distributed spatially according to the emissions allocated to sites of the respective industry branch and country.[9]

Non-energy intensive industries and process applications: For non-energy intensive industries such as Food and Tobacco, the number of facilities and share of emissions covered by installations in the merged emissions database is low compared to most energy intensive industry branches [28], [37]. The share of energy distributed via industry installations listed in the merged database is therefore set to the share of total emissions covered by the merged database in the respective industry branches and country. The remaining energy consumption is distributed to NUTS-3 level via the number of employees.[10]

All industries and cross applications: Independent of the industry, the energy consumption of cross applications is distributed according to the number of employees

3 "Low-hanging fruits" electrification in Europe

In this section, low-temperature heating and hot water and process heat electrification measures are analyzed: costs, emissions and final energy consumption (3.1), electrification decarbonization efficiency (3.2) and the location of additional loads (3.3).

3.1 Electrification costs, emissions and final energy consumption

Figure 5 shows the additional electrical FEC and absolute annualized electrification costs in 2050. Electrification costs are calculated based on the methodology described in section 2.2. Total absolute annualized costs in 2050 range from -0.7 bn € (Sweden) to 8.4 bn € (Germany). For the case of Germany, industrial low temperature electrification costs amount to approximately one third of annual spending on the renewable energy levy (~25 bn €). The presented absolute annualized electrification costs and additional electricity demand include all measures, which lead to a reduction of GHG-emissions until 2050.

8 Installations added to the merged EU-ETS and E-PRTR database based on external sources are allocated the average emissions of installations in the same industry branch.
9 For countries without installations in these industry branches, the energy consumption is distributed according to employees.
10 The number of employees by industry branch is available at NUTS-2 level. Employees [29] are distributed from NUTS-2 to NUTS-3 regions by calculating the population share of each NUTS-3 area within a NUTS-2 region using data from [30].

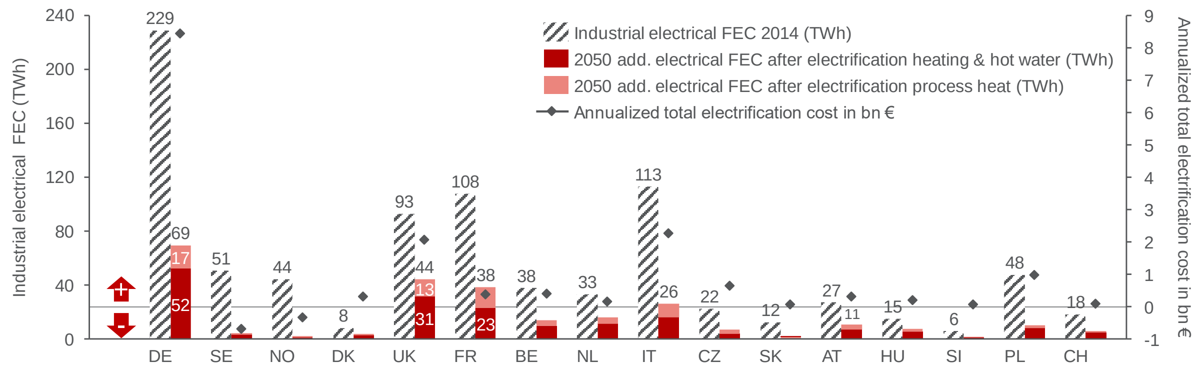

Figure 5: Electrical final energy consumption 2014, additional electrical final energy consumption (FEC) 2050 and total annualized electrification cost by country in 2050[11]

Across all analyzed electrification measures, which result in a reduction of CO_2 emissions until 2050, the share of OPEX of total annualized electrification costs is at least 92 %. This is in line with the results presented in [8] and shows that electrification costs react sensitively to changes in OPEX cost factors, such as energy prices. In all analyzed countries the wholesale price for electricity increases until 2050 as a result of increasing fuel and CO_2-certificate prices [23]. This however does not necessarily imply higher electrification costs. In addition to the electricity price, the development of the reference energy carrier prices (e.g. natural gas) as well as CO_2-certificate prices affect the OPEX of electrification measures. It is assumed, that companies classified as energy intensive (cf. Table 1 on page 7), are required to purchase emission certificates for the consumption of fossil fuels. Across all countries, electrification measures are therefore more cost effective in energy intensive compared to non-energy intensive industry branches. This effect is enhanced by the assumed electricity price structure where energy intensive industry branches are (partially) exempt from taxes, levies and surcharges, which results in electrification cost advantages.

Furthermore, Figure 5 shows the additional electrical FEC per country and application, in 2050. Compared to the current industrial FEC the largest relative increases occur in the Netherlands (48 %) and Great Britain (47 %). In both cases, the increase in electrical FEC due to the electrification of heating and hot water outweigh those coming from process heat electrification. Low increases in electrical FEC due to electrification in Norway (5 %) and Sweden (8 %) result from already high industrial biomass (Sweden) and electrification rates (Norway). In this context, an idea for further research is to analyze to what degree biomass could be redistributed to other European countries with less favorable conditions for producing emission free electricity. This in turn would affect the electrification potential in countries with high biomass usage.

11 The diagram only includes the additional electrical final energy consumption of measures that lead to a GHG-reduction in 2050.

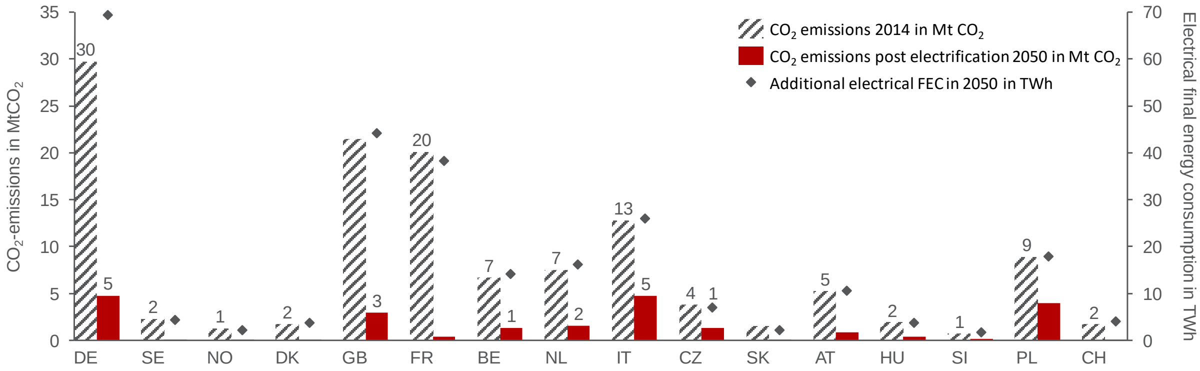

Figure 6: Low temperature process heat and heating and hot water emissions in 2014 and post electrification (2050) in Mt_{CO2} and additional electrical final energy consumption (FEC) in 2050 in TWh

Figure 6 depicts energy related CO_2 emissions before (2014) and after electrification (2050) and the absolute additional electrical FEC in 2050. The only country in which some electrification measures lead to an increase in CO_2 emissions in 2050 is Poland. The reason for this is the emission coefficient of power generation in 2050 (~220 g_{CO2}/kWh), which leads to higher emissions from electrification measures compared to the reference technologies, despite efficiency gains.[12] Across all electrified industry branches and applications in Poland, electrification leads to an emission reduction of 55 % compared to 2014. In Norway, CO_2 emissions drop as far as 99.7 % for the analyzed applications.

As shown in Figure 7, the analyzed electrification measures, which result in an emission reduction in 2050, can take a wide range of CO_2 abatement costs.

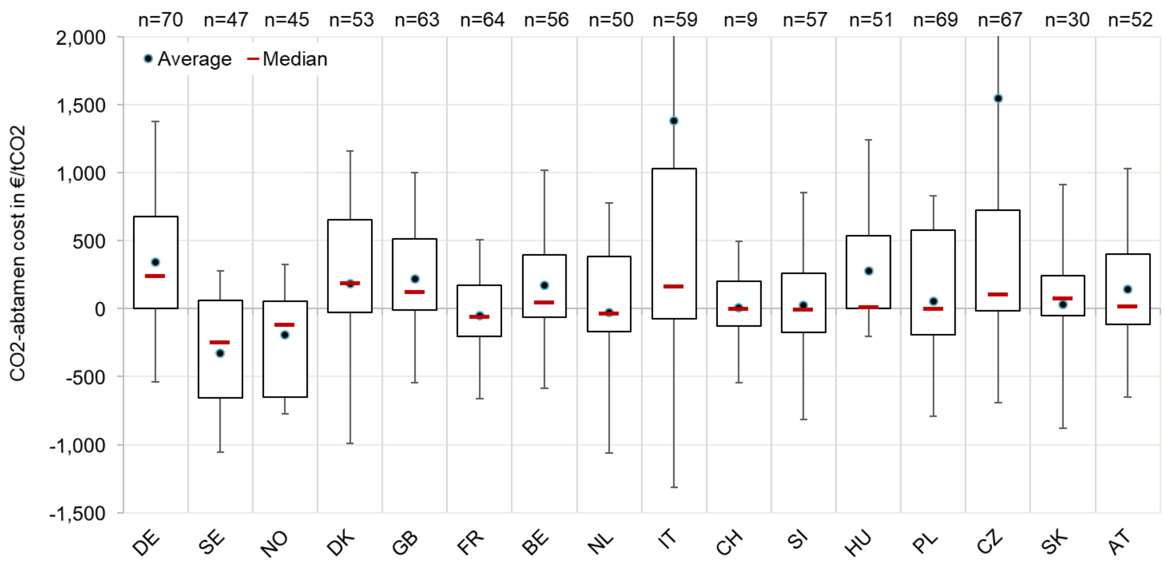

Figure 7: Range of CO_2-abatement costs for industrial electrification measures (<200 °C) in 2050 by country[13]

[12] Cf. the appendix for all emission factor assumptions.

13 The figure only contains data for measures that lead to an absolute emission reduction, which is greater than 1 t_{CO2}. The statistical data in Switzerland does not allow for a differentiation according to industry branches and temperature levels, which leads to a low number of calculated electrification measures. Maximum values are suppressed for visualization purposes.

Maximum values for Italy (7.700 €/t_{CO2}) and Czech Repulic (8.200 €/t_{CO2}) are not displayed for visualization purposes. All values greater than 210 €/t_{CO2} appear only in the temperature band between 100 °C and 200 °C, where electrification is performed using an electrode boiler. Due to the low efficiency of the electrode boiler compared to the heat pump covering the thermal energy demand results in a higher electrical FEC. This causes two effects, which lead to high GHG abatement costs: firstly, higher electricity consumption leads to increased OPEX compared to the reference technology. Secondly, in most countries (except for countries with very low emissions coefficients for power generation, such as example Norway, Sweden and France), a smaller emission difference between electrical and reference technology is achieved (cf. expression (2-5) on page 5). Both effects result in surging abatement costs. What is more, this shows that both very high and very low abatement costs not necessarily imply a large cost difference. The latter can also result from a very small emission difference, which calls for caution when interpreting these values.

In Figure 7 the highest abatement costs occur in industry branches, which are only partially exempt from taxes, levies and surcharges on the electricity price (i.e. Machinery, Mining and Quarrying, Transport Equipment). Negative abatement cost values mostly occur when industrial ground source heat pumps are used to supply heating and hot water or process heat below 100°C. Similar to high abatement cost values, the extreme negative values mainly occur at a low ratio of electricity to fossil energy prices and in classes where the emission difference is low. In Italy, the electrification cost minimum occurs for the electrification of heating and hot water in the iron and steel industry, where fuel oil is substituted through an electrical heat pump. In Italy the ratio of fuel oil to electricity prices increases significantly until 2050 (cf. Table 7 and Table 8 in the appendix).

3.2 Electrification decarbonization efficiency

Depending on the country, industry branch and reference energy carrier, the additional electrical FEC per ton of avoided CO_2 can vary drastically for the analyzed electrification measures. As shown in [1], additional electrical loads can result in challenges for the energy system (e.g. supply side capacity gaps or transmission network constraints). Figure 8 shows the electrification decarbonization efficiency derived as shown in section 3.2. The latter is defined as the additional electrical FEC per avoided ton of CO_2 and indicates the decarbonization efficiency of electrification measures from an energy system perspective.

In most countries, the median decarbonization efficiency is approximately 2 MWh/t_{CO2}. Hereby a comparison to high temperature as well as transport and household electrification measures poses an idea for further research. In the Czech Republic the median is ~5 MWh/t_{CO2}. This results from a variety of electrification measures in the temperature range between 100 – 200 °C, which cause a high additional electrical FEC at simultaneously low emission reductions. In all cases, the median is lower than the average, which shows that a small number of outliers skew the distribution of decarbonization efficiency values. When analyzing electrification from a system perspective these outliers should be viewed carefully, as they could lead to large increases in electrical FEC at simultaneously low emission savings.

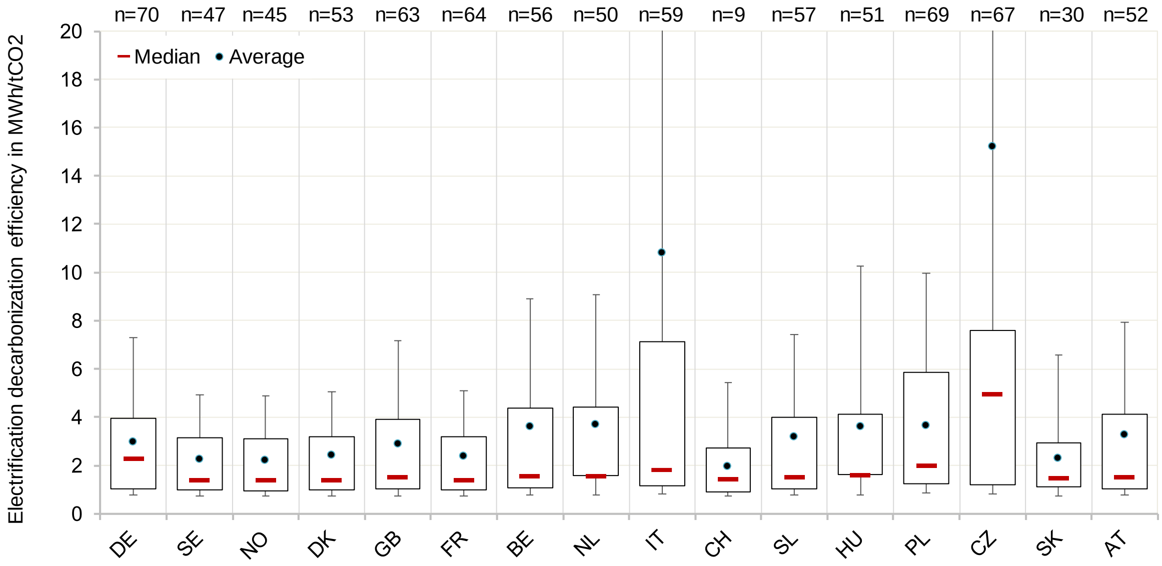

Figure 8: Range of electrification decarbonization efficiency (MWh/t_{CO2}) for industrial electrification measures (<200 °C) in 2050 by country[14]

3.3 Electrification in Nuts-3 resolution

In order to analyze the effect of electrification measures on the European energy system, the location of loads in relation to emission free electricity sources (mainly wind and solar power) is critical. Figure 9 shows the relative increase of electrical FEC in NUTS-3 resolution for all analyzed countries. The regionalization is based on the methodology described in section 2.3.

With respect to the electrification of low temperature process heat shown on the left hand side of the figure, it is noticeable that most NUTS-3 regions experience an increase of electrical FEC by 10 % or more. This results from the fact that the additional electrical loads predominantly occur in non-energy intensive industry branches, which are mainly regionalized via employee numbers. Furthermore, the map shows an approximately uniform distribution of additional electrical FEC in Switzerland because the statistical energy data for Switzerland does not allow for a differentiation according to industry branches. The additional electrical FEC for process heat is consequently regionalized fully via the number of employees.

The right hand side of Figure 9 shows the relative increase in electrical FEC for heating and hot water. The dark blue regions in the UK show a 40 % increase in electrical FEC in 2050 compared to 2014. In these regions, almost no electrical heating exists today. Due to the implemented regionalization of heating and hot water via the number of employees, these regions are assigned electrical FEC in 2050, leading to a drastic relative increase. The regionalization presented in Figure 9 builds the basis for evaluating the system effects of EU-wide electrification, which is the subject of further research.

14 The figure only contains data for measures that lead to an absolute emission reduction, which is greater than 1 t_{CO2}. The statistical data in Switzerland does not allow for a differentiation according to industry branches and temperature levels, which leads to a low number of calculated electrification measures. Maximum values are suppressed for visualization purposes.

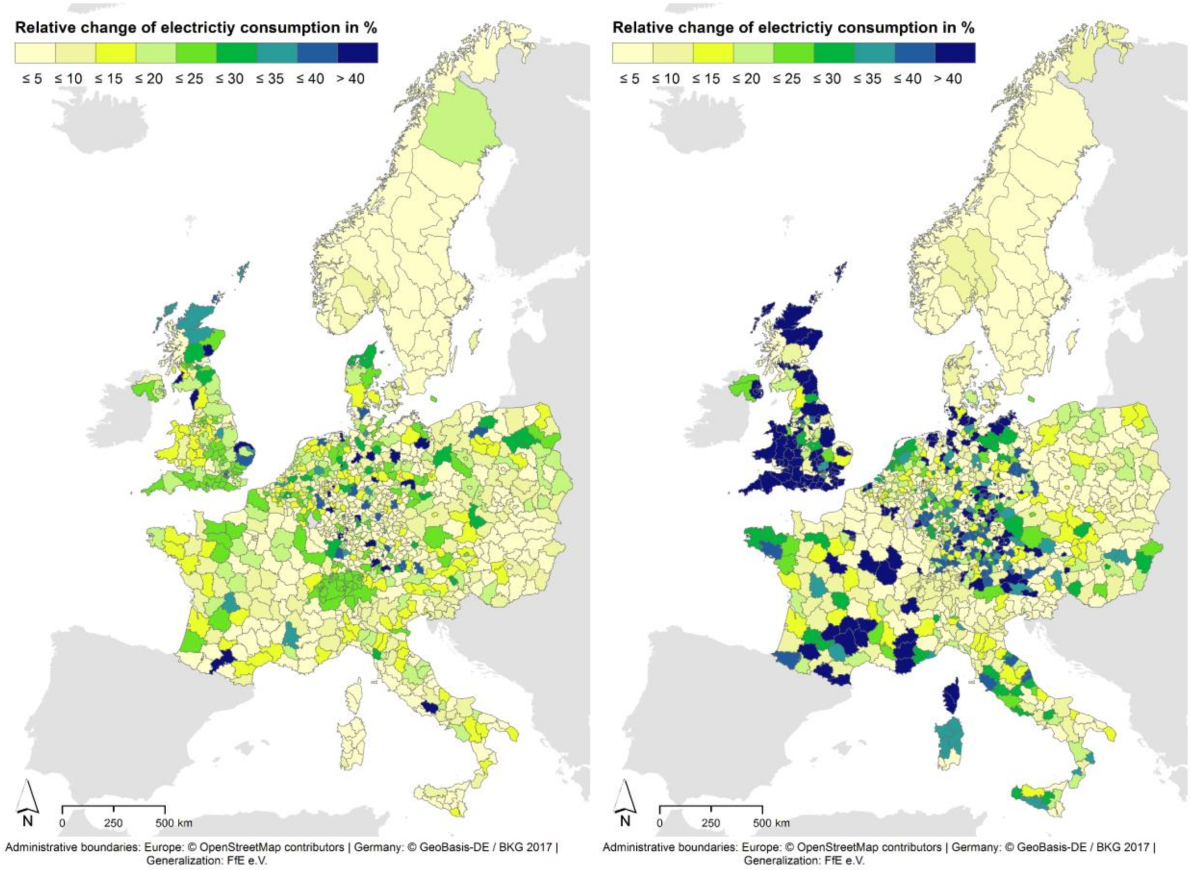

Figure 9: Regionalized (NUTS-3) relative change in electrical final energy consumption through the electrification of low temperature process heat (left side) and heating and hot water (right side)

4 Conclusion and ideas for further research

Based on the assumptions made in this paper, electrification leads to emission reductions in all analyzed countries by 2050. High electrification costs primarily occur in the temperature range between 100 °C and 200 °C, in which an electrode boiler is assumed as the electrical end-use technology. This could change if industrial heat pumps are implemented at higher temperature levels or if a combination of heat pump and electrode boiler is used. The only countries in which electrification using electrode boilers leads to avoided costs from an investor perspective are Sweden and Norway, as consumers profit from low electricity prices in these countries. In comparison, Italy experiences high electrification costs especially for non-energy intensive industry sectors due to high electricity prices resulting mainly from high taxes, levies and surcharges. Furthermore, the analysis shows that both positive and negative extreme abatement cost values (e.g. Italy) should be analyzed with care, as these values can result both from high costs and/or low emission differences.

In addition to the evaluation of electrification costs for industrial consumers, this paper proposes a new measure, which indicates possible system effects of electrification: the electrification decarbonization efficiency. This measure sets the additional electrical final energy consumption in relation to the avoided emissions through electrification. Considering that electrification is part of the decarbonization strategy in a variety of countries as well as a cross sectoral measure, the resulting additional electrical final energy consumption can be significant in certain regions. In addition to the costs of electrification, the decarbonization efficiency should therefore be considered when evaluating the feasibility of electrification measures. Similar to CO_2-abatement costs, electrification measures which cause very small emission differences result in extreme decarbonization efficiency values. The latter can be seen in Italy and Slovakia. Across the analyzed countries and electrification measures the range of medians of decarbonization efficiencies lies between 1 and 5 MWh/t_{CO2}.

The regionalization of industrial loads shows that existing and freely available industry site databases such as the EU ETS and E-PRTR do not allow for a full regionalization of industrial loads. A high share of the electrification measures analyzed in this paper is distributed via employee data. This might lead to a lower concentration of industrial leads in certain areas than expected in reality. Certain regions such as the south west of the United Kingdom experience relative increases of electrical final energy consumption after electrification of up to 40 %.

Ideas for further research result from the limitations of the work presented in this paper. Hereby primarily the system repercussions of high electrification rates should be analyzed. This can yield additional insights about electrification costs, avoided emissions and the decarbonization efficiency of individual measures. Furthermore, the additional electrical FEC should be compared to the positioning of renewable energy sources and the areas which exhibit renewable energy source potential. This can yield insights about the transmission task resulting from electrification.

5 Appendix

Table 3: Technology assumptions

Technology	Investment cost functions [€]	SPF/utilization [%]	Lifetime [years]
Heat pump[15]	$I_0 = 375\frac{€}{kW} * P$	350	20
Electrode boiler[15]	$I_0 = 150\frac{€}{kW} * P$	99	20
Oil boiler[16]	$I_0 = (2457 + 2582.6 * P^{0.5337})$	85 - 90	30
Coal boiler[17]	For $P = 200$ kW: $I_0 = 60\frac{€}{kW} * P$ For $P = 1500$ kW: $I_0 = 32\frac{€}{kW} * P$	80 - 85	30
Gas boiler[16]	$I_0 = (1228.5 + 1291.3 * P^{0.5337}) * (2.1348 - (6.1 * 10^{-6} * P))$	85 - 95	30

Table 4: Eurostat consumption categories and industry branch allocation[18]

Consumption category (GWh)	DE	NO	NL, HU, IT, DK, GB, FR, PL, SE, SK, SI	BE	CH	CZ	AT
0.5 < C < 2	2, 4, 6, 7, 8, 10, 11, 12, 13	4, 5, 6, 7, 8, 10, 11, 12, 13	4, 5, 6, 7, 8, 9, 10, 11, 12, 13	4, 6, 7, 8, 9, 10, 11, 12, 13	2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	4, 5, 6, 7, 8, 10, 11, 12, 13
2 < C < 20	5, 9	9	2	2, 5			2, 9
20 < C < 70		2					
70 < C < 150	1, 3						

15 [49].
16 [50].
17 [51].
18 1=Iron & steel industry, 2=Chemical & Petrochemical industry, 3=Non-ferrous metal industry, 4=Non-metallic Minerals, 5=Transport Equipment, 6=Machinery, 7=Mining and Quarrying, 8=Food and Tobacco, 9=Paper, Pulp and Print, 10=Wood and Wood Products, 11=Construction, 12=Textile and Leather, 13=Non-specified (Industry).

Table 5: CO_2-emission factors of fossil fuels and electricity generation of selected countries

	CO_2-emission factors of fossil fuels [g_{CO2}/kWh][19]				Simulation results: CO_2-emission factors of electricity generation [g_{CO2}/kWh]					
Country	Gas	Heating gas oil	Fuel oil	Coal	2015[20]	2020	2025	2030	2040	2050
Austria	198	266	293	337	155	73	99	77	92	80
Belgium					195	25	149	160	136	94
Czech Republic					530	404	337	248	222	191
Denmark					340	71,5	24	13,5	5,5	8,5
France					50	23	14	22	16	10
Germany					485	342	320	228	92	69
Hungary					305	304	195	73	69	109
Italy					365	327	312	265	216	182
Netherlands					610	391	315	236	165	96
Norway					10	1	4	4	3	2
Poland					795	679	652	490	330	222
Slovakia					150	102	89	32	42	54
Slovenia					320	148	22	56	53	72
Sweden					30	4	5	3	3	4
Switzerland					25	1	14	20	23	23
United Kingdom					320	204	135	104	79	67

19 [52].
20 [53].

Table 6: Energy carrier price assumptions and sources

Energy carrier	Assumptions	Relevant sources
Coal	German prices were assumed for all countries. Constant prices across all industry branches	All countries: 2015 [38]; 2025, 2030, 2035 [39] Scenario B; 2030 until 2050 [24];
Electricity	System cost of electricity is a simulation result. Taxes, levies and surcharges assumed constant over time. Switzerland: constant prices across all industry branches	All countries: System cost [23] All countries: [13] table nrg_pc_205 Switzerland: [40]
Gas	All countries: if gas prices for certain industry categories do not exist, the gas price of the closest category is used Switzerland and Norway: constant prices across all industry branches Norway: Gas price based on cross border prices of surrounding countries	All countries: [13] table nrg_pc_203 Switzerland: [41] Norway: OECD-01 18 and [42]
Oil	Constant prices for light and heavy fuel oil for all industry branches within a country Switzerland and Norway: ratio of heavy to light fuel oil prices set to average ratio of all other countries	All countries: [43] Norway: [44] Switzerland: [45]

Table 7: Energy carrier prices for industrial consumers in selected countries[21]

€/MWh	2015			2020			2025			2030			2040			2050		
Country	Coal[22]	HGO[23]	FO[23]	Coal	HGO	FO	Coal	HGO	FO	Coal	HGO	FO	Coal	HGO	FO	Coal	HGO	FO
Austria	14.9	72.1	31.6	17.4	108.1	47.4	19.9	144.2	63.1	20.4	158.6	69.4	21.4	180.2	78.9	22.4	187.4	82.1
Belgium	14.9	58.8	24.4	17.4	88.2	36.5	19.9	117.6	48.7	20.4	129.4	53.6	21.4	147.0	60.9	22.4	152.9	63.3
Czech Republic	14.9	68.1	52.4	17.4	102.2	78.6	19.9	136.3	104.8	20.4	149.9	115.3	21.4	170.3	131.0	22.4	177.1	136.2
Denmark	14.9	124.9	70.7	17.4	187.3	106.1	19.9	249.8	141.4	20.4	274.7	155.6	21.4	312.2	176.8	22.4	324.7	183.9
France	14.9	71.6	60.7	17.4	107.4	91.1	19.9	143.2	121.4	20.4	157.5	133.6	21.4	179.0	151.8	22.4	186.2	157.9
Germany	14.9	63.4	25.7	17.4	95.0	38.6	19.9	126.7	51.4	20.4	139.4	56.6	21.4	158.4	64.3	22.4	164.7	66.8
Hungary	14.9	117.1	40.8	17.4	175.6	61.3	19.9	234.2	81.7	20.4	257.6	89.8	21.4	292.7	102.1	22.4	304.4	106.2
Italy	14.9	120.3	31.6	17.4	180.5	47.3	19.9	240.7	63.1	20.4	264.8	69.4	21.4	300.9	78.9	22.4	312.9	82.0
Netherlands	14.9	103.7	44.7	17.4	155.5	67.1	19.9	207.3	89.5	20.4	228.0	98.4	21.4	259.1	111.8	22.4	269.5	116.3
Norway[24]	14.9	82.5	41.6	17.4	123.8	62.3	19.9	165.0	83.1	20.4	181.5	91.4	21.4	206.3	103.9	22.4	214.5	108.0
Poland	14.9	70.8	36.6	17.4	106.2	54.9	19.9	141.7	73.3	20.4	155.	80.6	21.4	177.1	91.6	22.4	184.2	95.2
Slovakia[25]	14.9	99.9	40.5	17.4	149.9	60.8	19.9	199.8	81.1	20.4	219.8	89.2	21.4	249.8	101.3	22.4	259.8	105.4
Slovenia	14.9	85.8	44.0	17.4	128.7	66.0	19.9	171.6	88.0	20.4	188.7	96.8	21.4	214.5	110.0	22.4	223.1	114.4
Sweden	14.9	111.3	73.1	17.4	166.9	109.7	19.9	222.6	146.3	20.4	244.8	160.9	21.4	278.2	182.8	22.4	289.3	190.2
Switzerland[26]	14.9	65.5	29.4	17.4	98.2	44.2	19.9	131.0	58.9	20.4	144.0	64.8	21.4	163.7	73.6	22.4	170.2	76.6
United Kingdom	14.9	63.6	38.7	17.4	95.3	58.1	19.9	127.1	77.4	20.4	139.9	85.2	21.4	158.9	96.8	22.4	165.3	100.6

21 Prices until 2050 are estimated based on the current policies scenario of World Energy Outlook 2016 [54].
22 All countries: 2015 [38]; 2025, 2030, 2035 [39] Scenario B; 2030 until 2050 [24].
23 HGO = Heating gas oil; FO = Fuel oil; Weekly Oil Bulletin – European Commission [43].
24 [44].
25 For Slovakia the latest released heating oil prices from 2011 were used.
26 [55].

Table 8: Electricity price components in years 2015, 2020 and 2050

Country	Consumption category (GWh)	Electricity price components for industrial consumers [€/MWh] Simulation results: System cost in year			Supply cost[27]	Network cost[27]	Taxes[27] (excl. VAT)	Value Added Tax[27]	Consumer price in year		
		2015[28]	2020	2050	constant	constant	constant	constant	2015[29]	2020	2050
Austria	C < 0.02	31.8	49.7	90.7	37.4	48.3	42.6	32.5	192.5	210.5	251.4
	0.02 < C < 0.5				22.0	37.5	33.1	25.3	149.6	167.6	208.6
	0.5 < C < 2				23.0	20.9	28.7	21.1	125.4	143.3	184.3
	2 < C < 20				15.7	18.1	24.8	18.2	108.5	126.5	167.4
	20 < C < 70				13.9	9.7	21.7	15.6	92.6	110.6	151.5
	70 < C < 150				9.7	8.8	19.7	14.1	84.0	102.0	143.0
Belgium	C < 0.02	44.9	49.7	70.1	22.8	69.6	40.1	34.3	211.7	216.5	236.8
	0.02 < C < 0.5				10.3	56.6	32.7	28.0	172.5	177.3	197.6
	0.5 < C < 2				8.0	26.2	30.0	20.9	129.9	134.7	155.0
	2 < C < 20				1.8	23.1	26.5	18.5	114.9	119.6	140.0
	20 < C < 70				12.6	12.0	7.3	15.3	92.0	96.8	117.1
	70 < C < 150				3.7	10.1	6.2	13.1	78.0	82.8	103.1
Czech Republic	C < 0.02	32.4	51.1	105.5	31.0	66.5	26.6	32.9	189.5	208.2	262.6
	0.02 < C < 0.5				16.8	51.6	20.7	25.5	147.0	165.7	220.1
	0.5 < C < 2				6.9	17.9	20.6	16.3	94.1	112.8	167.2
	2 < C < 20				3.9	16.5	19.1	15.1	87.0	105.7	160.1
	20 < C < 70				4.4	18.6	18.6	15.6	89.5	108.2	162.7
	70 < C < 150				5.3	19.0	19.0	16.0	91.7	110.4	164.9
Denmark	C < 0.02	23.7	49.4	72.9	42.0	55.9	57.7	106.3	285.5	311.2	334.7
	0.02 < C < 0.5				11.6	30.0	30.9	170.7	266.8	292.5	316.0
	0.5 < C < 2				12.2	24.3	29.7	168.9	258.8	284.5	308.0
	2 < C < 20				12.2	24.2	29.6	168.9	258.6	284.3	307.8
	20 < C < 70				7.0	15.5	31.1	165.9	243.2	268.9	292.4
	70 < C < 150				6.4	15.2	30.5	165.5	241.3	267.0	290.5

27 [56], [57] and [58].
28 [59], [60], [61] and [62].
29 [13].

France	C < 0.02	38.7	41.5	69.7	24.6	51.2	35.4	27.2	177.1	179.9	208.1
	0.02 < C < 0.5				12.2	41.2	28.5	24.1	144.5	147.4	175.6
	0.5 < C < 2				18.2	18.3	23.7	19.8	118.7	121.5	149.7
	2 < C < 20				11.4	16.1	20.9	17.4	104.5	107.3	135.5
	20 < C < 70				14.7	11.6	9.8	14.8	89.6	92.4	120.6
	70 < C < 150				4.6	9.4	7.9	11.9	72.4	75.2	103.4
Germany	C < 0.02	31.7	47.4	75.6	50.5	53.7	82.1	59.9	277.8	293.5	321.7
	0.02 < C < 0.5				33.5	42.6	65.2	51.3	224.2	240.0	268.1
	0.5 < C < 2				20.9	26.3	71.3	46.9	197.0	212.7	240.8
	2 < C < 20				14.1	22.9	62.1	43.2	174.0	189.7	217.8
	20 < C < 70				14.7	17.9	46.9	39.5	150.7	166.4	194.6
	70 < C < 150				8.8	15.6	41.0	36.9	133.9	149.6	177.8
Hungary	C < 0.02	40.5	51.7	105.6	14.6	33.2	18.2	26.8	133.2	144.3	198.2
	0.02 < C < 0.5				9.4	30.0	16.5	24.1	120.4	131.5	185.5
	0.5 < C < 2				8.1	21.7	16.5	21.4	108.2	119.3	173.3
	2 < C < 20				7.2	21.3	16.2	20.9	106.2	117.3	171.3
	20 < C < 70				5.0	21.9	16.4	20.7	104.6	115.8	169.7
	70 < C < 150				5.5	22.1	16.6	20.9	105.6	116.7	170.6
Italy	C < 0.02	52.3	53.7	97.7	66.0	40.3	108.9	53.5	321.0	322.4	366.4
	0.02 < C < 0.5				30.3	28.2	76.0	37.0	223.8	225.2	269.1
	0.5 < C < 2				25.4	16.8	65.7	26.2	186.4	187.8	231.8
	2 < C < 20				19.8	15.6	61.0	17.5	166.2	167.6	211.5
	20 < C < 70				20.5	7.6	45.6	11.8	137.8	139.2	183.1
	70 < C < 150				8.3	6.3	38.0	8.4	113.3	114.7	158.7
Netherlands	C < 0.02	40.1	50.1	69.0	30.8	35.9	71.8	37.7	216.3	226.2	245.1
	0.02 < C < 0.5				9.0	24.9	49.7	26.1	149.7	159.6	178.6
	0.5 < C < 2				13.2	18.8	15.3	18.4	105.8	115.7	134.6
	2 < C < 20				9.1	17.4	14.1	17.0	97.7	107.6	126.5
	20 < C < 70				4.5	18.4	3.7	14.1	80.8	90.7	109.7
	70 < C < 150				5.8	19.0	3.8	14.5	83.2	93.1	112.0
Norway	C < 0.02	24.0	49.8	63.7	3.7	31.7	16.6	18.4	94.4	120.2	134.1
	0.02 < C < 0.5				3.6	31.6	16.5	18.4	94.0	119.8	133.8
	0.5 < C < 2				18.7	20.1	12.5	18.2	93.5	119.3	133.2
	2 < C < 20				10.7	16.0	10.0	14.5	75.2	101.0	114.9

	20 < C < 70				3.4	5.4	17.2	11.9	61.8	87.6	101.5
	70 < C < 150				1.5	5.0	15.9	10.9	57.3	83.0	97.0
Poland	C < 0.02	37.8	52.4	91.1	38.3	69.3	6.1	35.0	186.4	201.0	239.7
	0.02 < C < 0.5				19.5	52.2	4.6	26.4	140.4	155.0	193.7
	0.5 < C < 2				18.8	25.7	4.8	20.1	107.2	121.8	160.5
	2 < C < 20				11.6	22.4	4.2	17.5	93.5	108.0	146.7
	20 < C < 70				10.5	15.6	5.2	16.0	85.1	99.6	138.3
	70 < C < 150				7.1	14.5	4.8	14.9	79.1	93.6	132.4
Slovakia	C < 0.02	33.7	51.1	103.6	19.3	102.9	53.0	41.6	250.4	267.8	320.3
	0.02 < C < 0.5				2.1	68.3	35.2	27.6	166.9	184.3	236.8
	0.5 < C < 2				4.9	39.9	36.0	22.5	136.9	154.2	206.7
	2 < C < 20				0.8	35.4	31.9	20.0	121.8	139.1	191.6
	20 < C < 70				5.5	16.7	38.6	18.6	113.1	130.5	183.0
	70 < C < 150				6.3	17.1	39.4	19.0	115.6	132.9	185.5
Slovenia	C < 0.02	41.4	51.7	105.9	31.2	52.5	18.0	31.7	174.7	185.0	239.3
	0.02 < C < 0.5				11.6	38.3	13.1	23.1	127.5	137.8	192.0
	0.5 < C < 2				15.4	17.4	10.6	18.7	103.5	113.8	168.0
	2 < C < 20				8.0	15.1	9.2	16.3	90.1	100.3	154.6
	20 < C < 70				6.1	9.4	7.8	14.3	79.1	89.3	143.6
	70 < C < 150				4.6	9.1	7.6	13.9	76.5	86.7	141.0
Sweden	C < 0.02	22.1	49.9	73.5	48.5	63.2	2.0	34.0	169.9	197.7	221.3
	0.02 < C < 0.5				14.9	33.1	1.1	17.9	89.0	116.8	140.4
	0.5 < C < 2				18.5	19.7	0.3	15.2	75.8	103.6	127.2
	2 < C < 20				13.4	17.2	0.3	13.3	66.3	94.0	117.6
	20 < C < 70				16.5	6.7	0.7	11.6	57.7	85.4	109.0
	70 < C < 150				9.7	5.5	0.6	9.5	47.4	75.1	98.7
Switzerland[30]	C < 0.02	46.3	49.4	86.2	13.0	57.6	21.2	25.0	163.0	166.1	202.9
	0.02 < C < 0.5				13.0	57.6	21.2	25.0	163.0	166.1	202.9
	0.5 < C < 2				14.0	36.2	15.5	18.0	130.0	133.1	169.9
	2 < C < 20				14.0	36.2	15.5	18.0	130.0	133.1	169.9
	20 < C < 70				5.5	33.9	15.3	18.0	119.0	122.1	158.9
	70 < C < 150				5.5	33.9	15.3	18.0	119.0	122.1	158.9

30 Consumer prices and components of consumer prices are gathered from [63].

United Kingdom	C < 0.02	56.1	54.5	64.2	53.5	39.6	34.1	37.0	220.2	218.6	228.3
	0.02 < C < 0.5				44.1	36.2	31.2	33.6	201.2	199.6	209.3
	0.5 < C < 2				28.2	35.4	30.8	30.1	180.6	178.9	188.7
	2 < C < 20				21.3	32.5	28.4	27.6	165.9	164.3	174.0
	20 < C < 70				21.4	31.0	25.6	26.9	161.0	159.4	169.1
	70 < C < 150				19.5	30.2	25.0	26.3	157.0	155.4	165.1

Table 9: Natural gas price components in years 2015, 2020 and 2050

		Natural gas price components for industrial consumers [€/MWh]									
Country	Consumption category (TJ)	Simulation result System cost in year			Supply cost[31]	Network cost[27]	Taxes[27] (excl. VAT)	Value Added Tax[27]	Consumer price in year		
		2015[32]	2020	2050	constant	constant	constant	constant	2015[33]	2020	2050
Austria	C < 1	20.6	23.2	28.7	14.7	6.5	12.8	11.5	66.2	68.7	74.2
	1 < C < 10				8.7	5.4	10.6	9.4	54.7	57.2	62.7
	10 < C < 100				4.4	4.6	9.0	9.1	47.8	50.3	55.8
	100 < C < 1000				1.8	1.3	9.6	7.7	41.1	43.6	49.1
	1000 < C < 4000				2.1	1.3	9.8	9.3	43.1	45.6	51.1
	4000 < C				-	-	-	-	-	-	-
Belgium	C < 1	20.0	22.4	27.8	18.0	4.1	3.9	9.5	55.5	57.9	63.3
	1 < C < 10				10.2	3.3	3.1	7.6	44.2	46.6	52.0
	10 < C < 100				4.0	2.6	2.5	5.9	34.9	37.3	42.7
	100 < C < 1000				2.2	0.6	2.7	4.3	29.8	32.2	37.6
	1000 < C < 4000				-	-	-	-	-	-	-
	4000 < C				-	-	-	-	-	-	-
Czech Republic	C < 1	21.3	23.9	29.6	8.7	8.9	1.8	8.6	49.3	51.9	57.6
	1 < C < 10				2.7	7.1	1.5	6.8	39.4	42.0	47.7
	10 < C < 100				0.5	6.5	1.3	6.2	35.8	38.4	44.1

31 [56], [57] and [58].
32 [64].
33 [13].

	100 < C < 1000				-	-	-	-	-	-	-
	1000 < C < 4000				-	-	-	-	-	-	-
	4000 < C				-	-	-	-	-	-	-
Denmark	C < 1	20.0	22.4	27.8	20.3	6.6	15.9	22.0	84.7	87.2	92.5
	1 < C < 10				15.2	5.7	13.9	25.9	80.7	83.2	88.5
	10 < C < 100				4.4	4.0	9.6	33.6	71.6	74.0	79.4
	100 < C < 1000				5.5	2.5	4.0	37.1	69.1	71.5	76.9
	1000 < C < 4000				2.9	2.3	3.6	38.5	67.2	69.6	75.0
	4000 < C				-	-	-	-	-	-	-
France	C < 1	20.6	23.2	28.7	18.6	12.1	3.8	10.0	65.0	67.6	73.1
	1 < C < 10				10.9	9.7	3.1	8.2	52.5	55.1	60.6
	10 < C < 100				5.9	8.1	2.6	6.2	43.4	46.0	51.5
	100 < C < 1000				4.6	3.1	1.5	4.3	34.1	36.6	42.1
	1000 < C < 4000				0.6	2.6	1.2	2.6	27.7	30.3	35.8
	4000 < C				-	-	-	-	-	-	-
Germany	C < 1	20.3	22.8	28.2	15.1	7.3	5.0	9.1	56.8	59.3	64.7
	1 < C < 10				11.4	6.6	4.5	8.2	50.9	53.4	58.8
	10 < C < 100				8.4	6.0	4.0	7.4	46.0	48.5	53.9
	100 < C < 1000				5.5	0.8	4.3	5.9	36.7	39.2	44.6
	1000 < C < 4000				2.9	0.7	3.9	5.3	33.0	35.5	40.9
	4000 < C				1.6	0.7	3.6	5.0	31.1	33.6	39.0
Hungary	C < 1	22.7	25.5	31.5	7.7	6.3	1.9	10.5	49.2	52.0	58.0
	1 < C < 10				8.5	6.5	2.0	10.7	50.3	53.1	59.1
	10 < C < 100				5.0	5.8	1.8	9.5	44.8	47.6	53.6
	100 < C < 1000				0.9	3.3	1.7	7.7	36.3	39.1	45.1
	1000 < C < 4000				1.0	3.3	1.7	7.7	36.3	39.1	45.1
	4000 < C				1.2	3.3	1.7	7.9	36.8	39.6	45.7
Italy	C < 1	22.7	25.5	31.5	22.5	9.6	5.4	11.9	71.9	74.8	80.8
	1 < C < 10				12.9	7.5	4.2	8.6	55.9	58.7	64.7
	10 < C < 100				2.6	5.4	3.0	4.0	37.6	40.4	46.5

	100 < C < 1000				4.1	0.6	1.1	2.2	30.7	33.5	39.5
	1000 < C < 4000				2.6	0.5	1.1	1.9	28.8	31.6	37.7
	4000 < C				2.0	0.5	1.0	2.3	28.6	31.4	37.4
Netherlands	C < 1	19.8	22.3	27.6	20.3	1.5	19.0	12.8	73.5	75.9	81.2
	1 < C < 10				17.1	1.4	17.5	11.7	67.5	70.0	75.3
	10 < C < 100				3.7	0.9	11.1	7.4	42.9	45.4	50.7
	100 < C < 1000				5.3	1.1	2.1	6.0	34.4	36.9	42.2
	1000 < C < 4000				3.3	1.0	2.0	5.5	31.7	34.1	39.4
	4000 < C				-	-	-	-	-	-	-
Norway[34]	C < 1	19.5	21.9	27.1	8.3	1.0	13.2	18.0	60.0	62.4	67.6
	1 < C < 10				8.3	1.0	13.2	18.0	60.0	62.4	67.6
	10 < C < 100				8.3	1.0	13.2	18.0	60.0	62.4	67.6
	100 < C < 1000				17.7	1.7	3.1	18.0	60.0	62.4	67.6
	1000 < C < 4000				17.7	1.7	3.1	18.0	60.0	62.4	67.6
	4000 < C				17.7	1.7	3.1	18.0	60.0	62.4	67.6
Poland	C < 1	21.3	23.9	29.6	11.5	9.4	0.9	9.9	53.0	55.6	61.3
	1 < C < 10				10.3	9.1	0.8	9.5	50.9	53.5	59.2
	10 < C < 100				5.8	7.8	0.7	8.3	43.9	46.5	52.2
	100 < C < 1000				7.8	1.7	0.0	7.1	37.8	40.4	46.1
	1000 < C < 4000				2.5	1.4	0.0	5.9	31.0	33.6	39.3
	4000 < C				-	-	-	-	-	-	-
Slovakia	C < 1	21.6	24.3	30	13.0	10.5	1.9	9.4	56.3	59.0	64.7
	1 < C < 10				7.7	8.9	1.6	7.9	47.7	50.4	56.1
	10 < C < 100				4.0	7.8	1.4	7.0	41.7	44.3	50.1
	100 < C < 1000				5.1	4.0	1.6	6.5	38.7	41.4	47.1
	1000 < C < 4000				3.5	3.8	1.5	6.1	36.4	39.1	44.8
	4000 < C				-	-	-	-	-	-	-

34 Consumer price for 2015 from [65].

Slovenia	C < 1	24.2	27.2	33.7	9.9	10.4	6.6	11.3	62.5	65.5	72.0
	1 < C < 10				9.5	10.3	6.5	11.2	61.8	64.7	71.2
	10 < C < 100				0.7	7.6	4.8	8.3	45.6	48.6	55.1
	100 < C < 1000				-	-	-	-	-	-	-
	1000 < C < 4000				-	-	-	-	-	-	-
	4000 < C				-	-	-	-	-	-	-
Sweden	C < 1	23.2	26.0	32.2	17.6	14.3	13.2	42.8	111.1	113.9	120.1
	1 < C < 10				9.5	11.5	10.6	39.4	94.2	97.0	103.2
	10 < C < 100				2.7	9.1	8.4	36.6	79.9	82.8	89.0
	100 < C < 1000				1.9	6.2	8.8	35.7	75.7	78.6	84.8
	1000 < C < 4000				1.2	6.0	8.5	35.5	74.3	77.2	83.4
	4000 < C				-	-	-	-	-	-	-
Switzerland[35]	C < 1	22.4	25.2	31.2	7.8	7.4	4.0	10.4	52.0	54.8	60.8
	1 < C < 10				7.8	7.4	4.0	10.4	52.0	54.8	60.8
	10 < C < 100				7.8	7.4	4.0	10.4	52.0	54.8	60.8
	100 < C < 1000				11.1	4.5	3.5	10.4	52.0	54.8	60.8
	1000 < C < 4000				11.1	4.5	3.5	10.4	52.0	54.8	60.8
	4000 < C				11.1	4.5	3.5	10.4	52.0	54.8	60.8
United Kingdom	C < 1	20.0	22.5	27.8	24.1	11.6	4.2	12.0	71.9	74.4	79.7
	1 < C < 10				9.3	7.7	2.8	8.0	47.8	50.2	55.6
	10 < C < 100				6.1	6.9	2.5	7.1	42.5	44.9	50.3
	100 < C < 1000				0.6	7.0	1.0	5.8	34.3	36.8	42.1
	1000 < C < 4000				-	-	-	-	-	-	-
	4000 < C				-	-	-	-	-	-	-

35 Consumer price for 2015 from [66].

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