A bottom-up estimation of heating and cooling demand in the European industry

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Abstract

Energy balances, e.g. the one provided by Eurostat, are usually aggregated at the level of subsector and energy carrier. In the context of transformation of energy systems and policies targeting energy efficiency as well as security of supply, more detailed information about the end-uses of energy is needed. While heating and cooling makes up for half the energy demand of the EU28 plus Norway, Switzerland, Iceland (EU28+3), balances aligned to Eurostat for the industrial sector, including process heat temperature level and end-use, are not available today. Here we present a methodology to disaggregate Eurostat's energy balance for the industrial sector and add these dimensions. Results show that though a stable overall pattern can be observed, considerable differences among countries in terms of temperature distribution, energy carrier use and their cross-references exist. These differences are mainly caused by heterogeneous economic structures of the countries in scope, highlighting that approaches on process level yield more differentiated results, which subsector level approaches cannot. We calculate the EU28+3 industrial process heating demand to 1,035 TWh, 706 TWh and 228 TWh at the respective temperature levels >500 °C (e.g. iron and steel production), 100–500 °C (e.g. steam use in chemical industry) and 100 °C (e.g. food industry). We expect the results presented here to contribute to policy design regarding energy efficiency and security of supply, by providing a deeper insight in the requirements and particularities of industrial heat demand.

Introduction and Motivation

Energy balances are an important tool for researchers and policy makers alike. The effort needed to generate primary data, however, limits them to rather aggregated levels. Usually, energy balances provide information on a sectoral and subsector level for individual or groups of energy carriers. The energy balance provided by Eurostat can be seen as reference for Europe, as it generates a harmonized framework for the data collected by the national statistical institutes of the member states. While virtually all member states of the EU generate national energy balances, availability of end-use balances, especially in the industry sector, is limited. Currently, also Eurostat does not provide end-use energy balances. EU regulation No 1099/2008 and its amendments demand "greater focus (…) on final energy consumption" and more detailed and comparable energy statistics (European Parliament 2008), thus, while not explicitly defining end-use dimensions, implying the need for data beyond the conventional dimensions subsector and energy carrier. Additionally, more detailed energy balances can help identifying relevant applications for focused energy efficiency research.

End-use balances break down the final energy demand in specified use categories as space and process heating/cooling, sanitary hot water and electrical appliances such as motors and lighting. Table 1 shows the type of end-use balance by fuel type available for space heating (S), hot water (H), appliances (A) and process heating/cooling ($P_{h/c}$). For industry, only Germany, Switzerland, United Kingdom and Austria provide more or less complete end-use balances with only Switzerland presenting data on all investigated categories.

This is not only related to the general problem of collecting detailed data on energy demand but can be attributed in particular to industry-specific issues: The evaluation of process

Table 1. Available national energy balances and end-use balances in the EU28 + NO, CH, IS (EU28+3), (source: Fraunhofer ISI).

Country	Energy balance	Industry end-use balance
Germany	X	S H A P_h
France	X	A P
Italy	X	H
Austria	X	S H A P_h
United Kingdom	X	S A $P_{h/c}$
Switzerland	X	S H A $P_{h/c}$

heat demand requires detailed knowledge about the characteristics of the various and numerous processes applied in the European industry, even more so does the allocation of temperature levels. And while individual processes, especially the ones with high overall or specific energy demand (energy intensive industries), are well researched in terms of energy efficiency, a complete picture requires a huge amount of data. When it is either not possible or desired to gather these in surveys, energy demand simulation models can be applied.

The mentioned issues, however, create the challenge that top-down approaches lack the desired level of detail while bottom-up approaches struggle with data availability.

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

Previous work on this topic includes Pardo et al. (2013), who used similar approaches to several questions, e.g. to assign a share of final energy for heating or temperature levels to industrial fuel use, though with an emphasis on energy transformation from primary to useful energy for the industrial, residential and tertiary sector in the EU27. He presents Sankey-diagrams with the dimensions subsector and temperature, stating distinct temperature profiles per subsector. His results show that natural gas, petroleum products and coal products cover 83 % of primary energy consumption. However, the absolute values provided are not immediately comparable to Eurostat's energy balance.

Naegler et al. (2015) presented two different approaches for the disaggregation of the final industrial energy demand of the EU28 in 2012, concluding that the data basis needs significant improvements to achieve robust results. They present industrial heat demand for EU28 between 8,149.8 and 8,517.5 PJ in five end-uses (space heating and hot water, four process heat temperature levels). However, due to limited access to national bottom-up data, they used the end-use structure from Germany, as it was available in its national end-use balance. They assume that processes are equal across countries. They show that many approaches on the disaggregation of energy demand in the EU28 rely on similar data sets, thus producing similar results. This implies that different approaches are needed to prove or challenge robustness of available studies.

We want to contribute to this effort by introducing an approach that includes differences in national economic structures and process-specific information. This allows us to create temperature-profiles for individual processes, which results in significant different temperature-profiles among the countries, as their economic structure differs. Thus, we reduce the dependency on single national end-use balances that neglect country-specific differences when applied to the entire EU28 and Norway, Iceland and Switzerland (named EU28+3 hereafter).

In section "Energy Disaggregation in the German End-Use Energy Balances", we present a common application of the energy demand model FORECAST, followed by a description of the model and important data assumptions in "Methodology and Data". Section "Results" presents different dimensions of the model results, which are discussed in the last section.

Energy Disaggregation in the German End-Use Energy Balances

As Germany is one of the few European Countries to publish detailed end-use energy balances, the German approach will be presented in more detail. The German energy balances are not published by the Federal Statistical Office (destatis) but by a working group which is dedicated to energy balances. This working group, the Arbeitsgemeinschaft Energiebilanzen (AGEB) prepares the energy statistic of Germany on behalf of the federal government of Germany. As a contractor for the Federal Ministry for Economic Affairs and Energy (BMWi), the AGEB provides the end-use energy balances. The different end-use sectors are covered by three research institutes: Transport and private Households are covered by RWI, the tertiary sector by TU München and industry by Fraunhofer ISI.

The end-use balances for the private households and the tertiary sector are based on energy use surveys, which are carried out regularly within those two sectors. For industry, such a survey is not available; therefore a different approach is taken.

The German energy balance for industry is quite comprehensive, as it differentiates the energy use of 14 sectors and 29 energy carriers. Based on this rather detailed disaggregation within the sector, the further disaggregation is made based on a combination of statistical and model based approaches.

Within the end-use energy balances of all sectors, the energy use is disaggregated within 7 major end uses. Some of the end-uses are disaggregated in more detail (**in bold**) within the end-use energy balances for industry:

1. **Space heating**
2. **Hot water**
3. **Process heating**
4. **Cooling**
    a. **Air conditioning**
    b. **Process cooling**
5. Mechanical energy (incl. electric drives)
    a. Compressed air systems
    b. Pumps
    c. Other mechanical energy

Table 2. Indicators for heating and cooling uses.

Air conditioning, space heating, hot water	Number and type of employees in the sector	Specific energy demand per employee (statistical)
Process cooling, process heating	Production indicators	Specific energy use of the relevant processes (technical, model based)

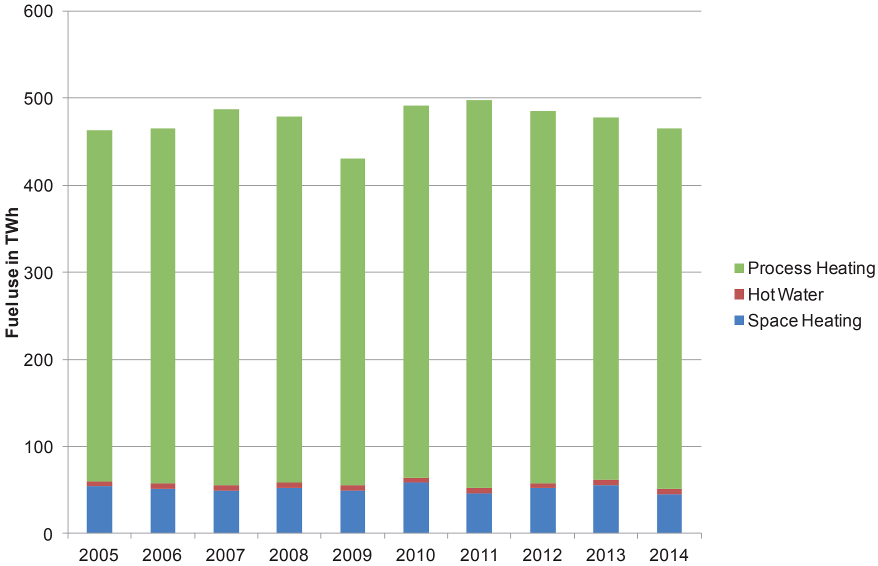

Figure 1. Disaggregation of fuel use in a time series from 2005–2014 in the German industry.

6. Lighting
7. Information and communication technology (ICT)

For all end uses, specific energy uses are combined with other parameters to assess the energy demand for the individual energy uses. Table 2 gives an overview of the indicators used for the heating and cooling uses. For the calculation of the overall balance, two kinds of indicators are distinguished:

1. Energy uses, which are mainly determined by the number of employees in the sector, such as space heating, hot water (not for process use), air conditioning, lighting and ICT and
2. Energy uses, which are mainly determined by the production volumes within the sectors, such as process heating (including hot water for process use) and cooling as well as mechanical energy.

For the first kind of energy uses, the energy demand for the end uses is calculated with a bottom up approach using the statistical indicators in combination with specific energy uses, which are derived from specific studies and modelling exercises. The HVAC related figures are adapted to the actual climate of the year to be compatible with the energy balance.

For the second kind of energy uses, the remaining energy use of the sectors is distributed to the energy uses with a model based allocation matrix using the statistical figures for the different products. The allocation matrix is calculated with the bottom-up energy demand model FORECAST-industry, which is presented later in this paper.

The result is a disaggregation of energy uses for fuels end electricity. On this level of the analysis, no differentiation of energy carriers is made. This differentiation is added in a second step. Therefore for each sector and energy use a specific allocation matrix for energy uses and energy carriers is used. With this allocation matrix, the energy uses are assigned to the different energy carriers. For example, mechanical energy for fuels is only assigned to mineral oils and gasses, as they are mainly used to drive motors. The resulting equation systems are solved iteratively to match the determined energy use split as well as the energy balance.

The final result is a split of the energy demand per sector, energy carrier and energy use. Figure 1 shows the disaggregation of fuel use in the German industry for heating uses based on the described methodology. The changes in the energy use for process heating are mainly due to economic effects, whereas for space heating, climatic changes are predominant. Energy efficiency effects can hardly be seen in such a short time series. The impact of energy efficiency on the split of energy uses is rather low, as the technological developments do not differ very much between the different end uses and other impacting factors like economic development and short time climatic effects are much more predominant.

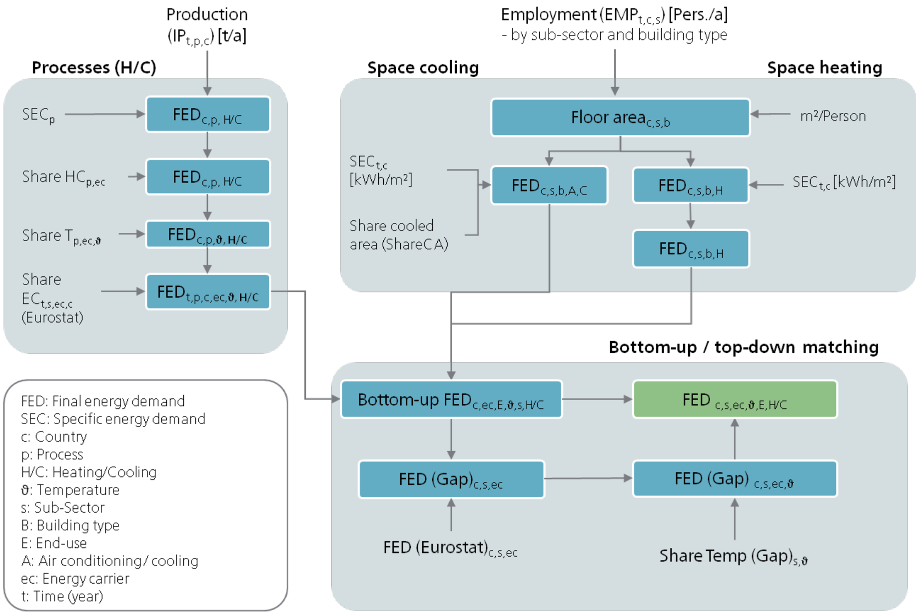

Figure 2. Schematic representation of the end-use balance model calculation for the industry-sector (FORECAST-Industry).

Methodology and Data

The model FORECAST-Industry works on the level of processes, subsectors, technologies and energy carriers. It is divided in three parts, which will be described following the model workflow: Processes, space heating/cooling and bottom-up/top-down matching (Figure 2). Processes and space heating/cooling are calculated in a bottom-up approach (top left/ right), based each on an activity-value and specific energy demand. The resulting bottom-up value is matched (bottom right) to top-down statistical values (i.e. Eurostat energy balance).

PROCESSES

The energy demand of the 64 most energy intensive industrial processes is calculated in a bottom-up approach as given in equation (1).

$$FED_{t,p,c,ec,\vartheta} = IP_{t,p,c} * SEC_p * ShareEC_{t,s,ec,c}$$

$$* ShareHC_{p,ec} * ShareT_{p,ec,\vartheta} \qquad (1)$$

With FED as final energy demand of a process, IP as its activity (production), SEC as specific energy demand (example processes are given in Table 3, complete list of processes available at (European Commission 2016)), ShareEC as energy carrier share (taken on subsector level from Eurostat energy balance), ShareH/C as share of heating and cooling demand on the total energy demand and ShareT as distribution of the energy demand among the temperature levels. The indices depict the dimensions of the respective factors: t for year, p for process, c for country, ec for energy carrier, ϑ for temperature.

Similarly, both Pardo et al. (2013) and Naegler et al. (2015) assign a share of the final energy to H/C purposes and temperature levels assuming similar shares across countries. However, both are allocating this information on the level of subsectors and cannot account for substantial structural differences across the countries within the subsectors, for example the sector iron and steel in Italy/Germany, with significant different shares of electric and oxygen steel. To overcome this weakness, we allocate the above mentioned shares not on the level of subsectors but on the level of 64 individual energy-intensive processes.

Although we also assume constant specific energy demand and temperature shares for all countries (since the processes are the same for all countries), this assumption is much more justified on the level of individual processes because these vary much less across countries.

Our definition of temperature levels is given in Table 4. Space heating is assumed to be supplied below 100 °C. Production is given in tonnes (various sources, e.g. (World Steel Association 2014), (EuroChlor 2015), see (European Commission 2016) for more), while the specific energy demand for fuel and electricity is in GJ/t. Note that by using country-specific data on activity, the industrial structure of the countries is reflected, allowing for significant differentiation, e.g. of temperature profile. The process characteristics (SEC, temperature profile) on the other hand, are assumed to be the same for all countries, so that process equals process. This is an approximation, since for example energy efficiency differences among the countries do exist. But it yields the possibility to keep the database manageable and to update it if necessary. Additionally, comprehensive data on efficiency differences among the countries on process level is not available. Our results indicate that for many processes, this assumption is good enough not to influence the results notably; yet we know of several processes (e.g. ethylene production, which may utilize different raw materials) that show distinct differences among countries.

In order to include temperature levels, we assume that all fuels are used to produce heat, stated in *ShareHC* in (1), while the major part of electricity is used in non-heat applications, an exception being electric arc furnaces in steel and calcium carbide production. We assume that other applications for fuel use (like direct mechanic energy) are negligible. On-site generation of electricity is, as of Eurostat energy balance definition,

Table 3. Example processes and their SEC and temperature distribution.

Process	Fuel use [GJ/t]	Electricity use [GJ/t]	15°C-75°C	75°C-100°C	100°C-125°C	125°C-150°C	150°C-200°C	200°C-500°C	500°C-1000°C	>1000°C	Eurostat subsector
Blast furnace	11.64	0.60						0.03	0.20	0.77	Iron and steel
Electric arc furnace	0.98	2.28							0.10	0.89	Iron and steel
Aluminum, primary	5.20	53.64							1.00		Non-ferrous metals
Aluminum foundries	7.20	5.60							1.00		Non-ferrous metals
Copper, primary	8.00	2.79								1.00	Non-ferrous metals
Chemical pulp	12.65	2.30			0.10	0.20	0.70				Paper and printing
Mechanical pulp	-2.01	7.92		1.00							Paper and printing
Container glass	5.78	1.41			0.06	0.06	0.08	0.19	0.30	0.30	Non-metallic mineral products
Clinker calcination-dry	3.50	0.14						0.10	0.60	0.30	Non-metallic mineral products
Bricks	1.40	0.20	0.10	0.10					0.60	0.20	Non-metallic mineral products
Ammonia	11.27	0.48							0.66	0.33	Chemical industry
Ethylene	35.90	0.00							1.00		Chemical industry
Methanol	15.03	0.49							0.22	0.78	Chemical industry
Dairy	1.57	0.53	0.45	0.45	0.03	0.03	0.03				Food, drink and tobacco
Brewing	0.97	0.39	0.28	0.28	0.15	0.15	0.15				Food, drink and tobacco
Bread & bakery	2.40	1.45	0.10	0.10	0.11	0.11	0.11	0.47			Food, drink and tobacco

Table 4. Definition of temperature levels for process cooling and process heating.

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

part of the transformation sector. Heat produced in combined heat and power production however, is included in the model.

Non-heat energy use (e.g. in cross-cutting technologies as motor appliances or lighting) is tracked to complete the energy balance, but not presented here.

SPACE HEATING/COOLING

$$FED_{t,c,s} = EMP_{t,c,s} * EMPArea_{c,s,b} * SEC_{t,c,b} * EH(C)I_c * ShareCA \quad (2)$$

Similar to the calculation of process energy demand, but on subsectoral level, final energy demand in space heating and cooling in industry (*FED*) is composed of an activity, employees (*EMP*) (Eurostat 2016-1) and a specific energy demand, heating/cooling demand per floor area (*SEC*). It is adjusted to countries using the European heating/cooling index EHI/ECI described by Werner (2006, 2015), (*EH(C)I*). In these publications, Werner states that specific energy demand is proportional to the square root of the heating/cooling degree days, rather than following a direct proportionality. Table 5 and Table 6 show example values of area per employee (*EMPArea*) and SEC.

As there are no comprehensive statistics about the floor area in industrial subsectors available, we calculate it based on the employment by sub-sector and the specific floor area per employee (*EMPArea*).We assume that this value varies among the countries, which is included with calibration factor. For cooling, we include an additional assumption about the share of cooled floor area (*ShareCA*). Indices depict year (*t*), country (*c*), building type (*b*) and subsector (*s*). Since in industry, data on space heating and cooling in general are scarce, the results are calibrated to top-down values given by Eurostat, while retaining subsectoral information on the distribution. Single values that seemed unreasonable high have been curtailed at 15 %.

BOTTOM-UP TOP-DOWN MATCHING

The bottom-up results for space and process heating/cooling (plus non-heat use) do not match the energy balance in most cases, since smaller processes and most electricity use (e.g. electrolysis or mechanical energy) are not included in the bottom-up calculation, just as input data might not be perfectly accurate. Since this difference, or gap, lacks the process-specific detail of the bottom-up calculation, high bottom-up coverage is a major quality criterion of our approach. Low bottom-up coverage in a subsector means that temperature distribution

Table 5. Area per employee in m² by subsector and building type.

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

Table 6. SEC for space heating by construction year and building type.

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

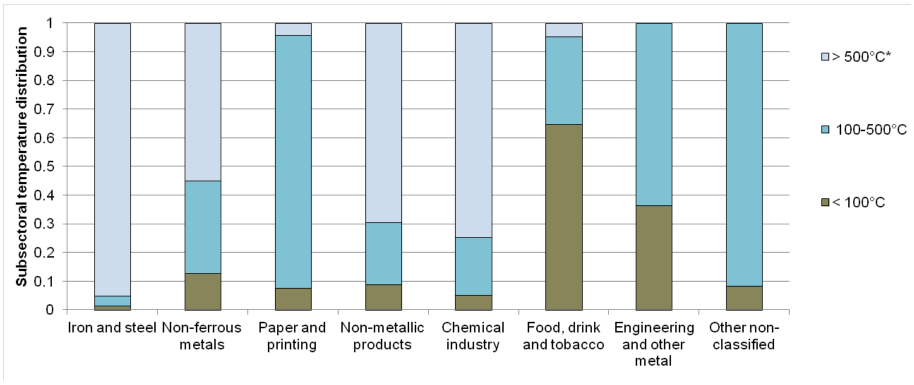

Figure 3. Subsector temperature distribution, used for energy demand not covered by bottom-up calculation.

defaults to subsector-specific values shown in Figure 3, which essentially resembles the above mentioned earlier approaches. Country-specific particularities are lost for this part of the energy demand.

Figure 4 shows the overall bottom-up coverage by subsectors for EU28+3, Figure 5 for each country (combined subsectors), including both bottom-up values processes and space heating. Where bottom-up coverage of more than 100 % occurs; which may be caused by overestimated activity, SEC, space heating demand or allocation differences in the used statistics, the above mentioned gap is negative. It is used to calibrate the results to the used energy balance (i.e. Eurostat).

Results

In this section, the main results are presented, focusing on the dimensions added to the Eurostat energy balance: temperature level (Table 4) and application (process heat, space heat, cooling).

Figure 6 shows the temperature distribution of the final energy demand by subsector for the EU28+3. From the 1,035 TWh of process heat above 500 °C, 96 % are used in the three subsectors iron and steel, basic chemicals and non-metallic minerals, with iron and steel alone contributing 48 % (493 TWh). Basic chemicals and non-metallic minerals follow with 25 % (260 TWh) and 23 % (240 TWh), respectively. This is mainly caused by the combination of high absolute energy demand and high temperature level, which is found in the following processes: Blast furnace, blast furnace-related processes and electric arc furnaces (iron and steel), clinker burning (non-metallic minerals) and ammonia production and ethylene (basic chemicals). The finding that these processes contribute most to the overall high temperature demand is consistent for the EU28. Note that this still varies for individual countries; there are for example countries that do not engage in blast furnace operations.

Table 7 shows the processes used in FORECAST. Processes with high absolute energy demand are underlined; high temperature level processes (>500 °C) are marked in bold. To define “high absolute energy demand”, we arbitrarily set a limit of at least 3 % of the bottom-up explained heating demand (ca. 90 %, 2,078 TWh)).

In Figure 6, process heat demand between 100 °C and 500 °C, which we assume to be the typical temperature range for steam systems, is most prevalent in the paper and printing subsector (217 TWh); as well as in other industries (203 TWh) that were not subject to detailed modelling on process level and whose results are therefore less robust. Notable other subsectors in this respect are non-metallic minerals (82 TWh), food, beverages and tobacco (78 TWh) and basic chemicals (51 TWh). Low temperature (<100 °C) process heating and space heating (574 TWh), characterized by the use of hot water, is mostly used in food, beverages and tobacco (24 %, 135 TWh), other industries (20 %, 114 TWh), machinery and transport (19 %, 111 TWh) and basic chemicals (18 %, 105 TWh).

Process and space cooling is, compared to heat demand, almost negligible. However, significant differences among the sectors are noticeable: Deep temperature (<-30 °C) occurs only in basic chemicals (20 TWh), in the context of air separation. Notable other cooling demand (66 TWh) exists in food, bever-

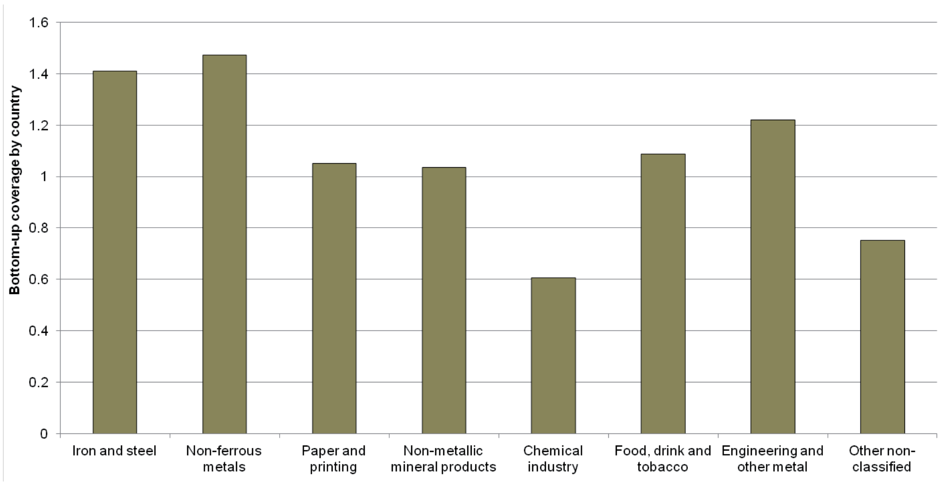

Figure 4. Bottom-up coverage by subsector for EU28+3, 1=100 %.

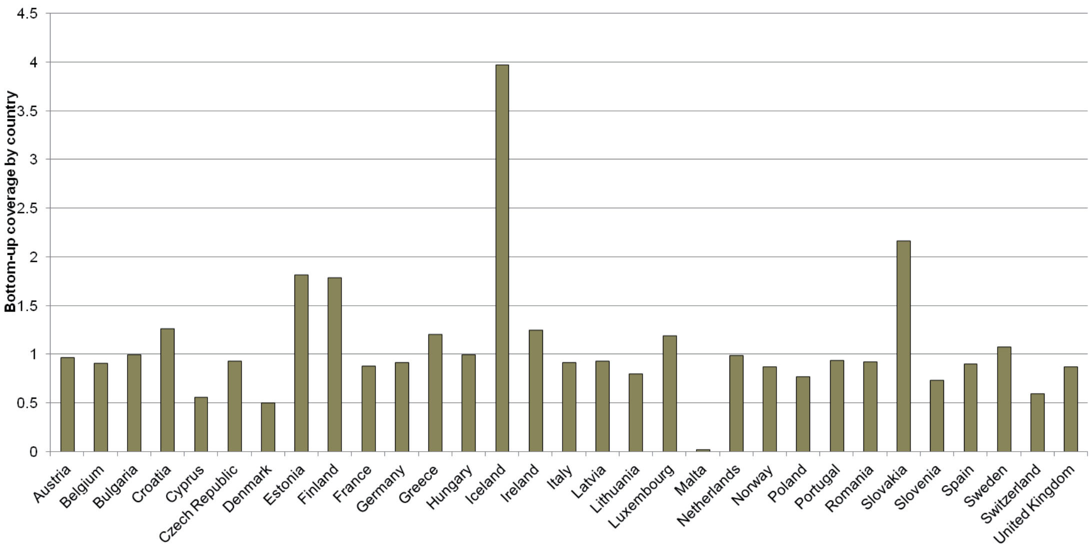

Figure 5. Bottom-up coverage by country, 1=100 %.

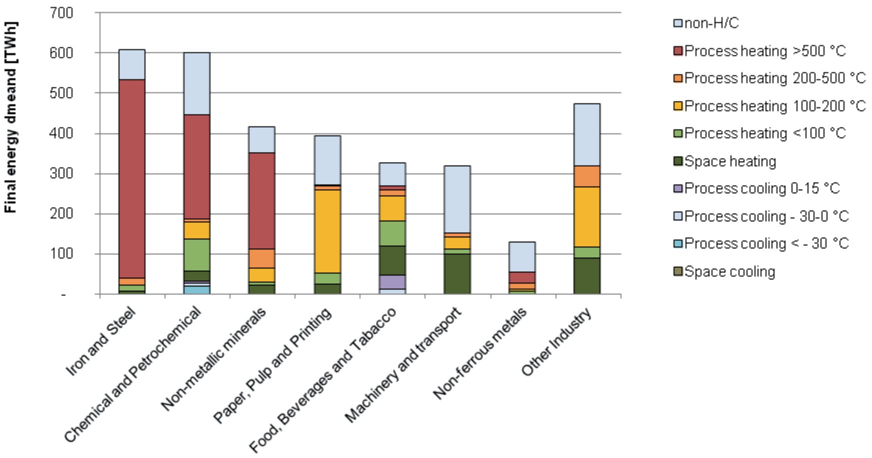

Figure 6. Final energy demand by subsector and temperature level EU28+3.

Table 7. Processes used in FORECAST: high absolute (>3 %) energy demand underlined; high temperature (>500 °C) processes marked in bold.

Non-metallic mineral products		Non-ferrous metals		Basic chemicals		Iron and steel	Other non-classified
Container glass	**Clinker calcination-semidry**	**<u>Aluminum, primary</u>**	**Zinc, primary**	Adipic acid	Nitric acid	**<u>Sinter</u>**	Extrusion
Flat glass	**Clinker calcination-wet**	Aluminum, secondary	Zinc, secondary	**<u>Ammonia</u>**	Oxygen	**<u>Blast furnace</u>**	Injection moulding
Fiber glass	Preparation of lime-stone	Aluminum extruding	**Food, beverages and tobacco**	**Calcium carbide**	Poly carbonate	**<u>Electric arc furnace</u>**	Blow moulding
Other glass	Gypsum	**Aluminum foundries**	Sugar	**Carbon black**	Poly ethylene	**<u>Rolled steel</u>**	**Paper and printing**
Houseware, sanitary ware	Cement grinding	Aluminum rolling	Dairy	Chlorine, diaphragm	Poly propylene	**<u>Coke oven</u>**	<u>Paper</u>
Technical, other ceramics	Lime milling	**Copper, primary**	Brewing	Chlorine, membrane	Poly sulfones	**Smelting reduction**	<u>Chemical pulp</u>
Tiles, plates, refractories	**Bricks**	**Copper, secondary**	<u>Meat processing</u>	**Chlorine, mercury**	Soda ash	**Direct reduction**	Mechanical pulp
<u>Clinker calci-nation-dry</u>	**Lime burning**	Copper further treatment	Bread & bakery	**<u>Ethylene</u>**	TDI		Recovered fibers
			Starch	**Methanol**	Titanium dioxide		

Table 8. Process and space heat demand by country and temperature level, cooling demand by country for EU28+3.

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

ages and tobacco (46 TWh), with the other subsectors combined summing up to only 19 TWh.

Figure 7 shows the temperature share (left ordinate, columns) and final energy demand for heating and cooling (right ordinate, line) by country for the EU28+3. Data is also presented in Table 8. A relatively stable temperature distribution among the countries can be observed. Exceptions are Iceland, Cyprus and Malta, which show remarkable high relative cooling demand share. This is caused by low data availability, often limited to electricity only or certain subsectors in terms of top-down energy demand. The same is true for activity data, limiting the reliability of our results for these countries in general. Another singularity is the high share of process heating between 100 and 200 °C in Sweden and Finland. This can be explained by the high importance of the pulp and paper industry in these countries, accounting for 33 % (58 TWh) and 27 % (50 TWh) of their total heating and cooling demand, respectively. Slovakia shows a high share of high temperature energy demand, which is caused by the iron and steel industry with 21.9 TWh (54 % of country total energy demand) above 500 °C. The same is true for Luxembourg (3.1 TWh above 500 °C, 53 % of country total).

Figure 8 shows energy carrier shares (left ordinate, columns) and total final energy demand for heating and cooling (right ordinate, line) for EU28+3. Most used energy carriers are natural gas (935 TWh, 39 % of total), coal (415 TWh, 17 %), other fossils (243 TWh, 10 %), biomass (216 TWh, 9 %), fuel oil (208 TWh, 9 %), district heat (184 TWh, 8 %) and electricity (173 TWh, 7 %). Germany, Italy, France, United Kingdom and Spain account for 57 % (1,374 TWh) of the total heating and cooling demand of the EU28+3 (2,401 TWh), while the smallest 14 sum to 11 % (253 TWh).

Discussion and Conclusions

To interpret the results of our approach, we compare it to a recent publication (Naegler et al. 2015). Due to similar methodology and some used data sets (e.g. ISI 2013, Eurostat 2016-2), it seems well suited to highlight the benefits of the detailed bottom-up data and the combination of empirical and modelling elements. Figure 9 directly compares the results of our approach and two data sets of (Naegler et al. 2015). In general, it appears that dataset 2 (DS-2) in (Naegler et al. 2015) is a closer match to our results, which is most likely related to the use of Eurostat energy balances, which we used too. The remaining differences are probably caused by different assumption about non-heating/cooling use, which is especially relevant for electricity. Note that our results match the Eurostat energy balance (Eurostat 2016-2) for 2012 on subsector and energy carrier level. There are, though, considerable differences in some countries; especially the comparably high absolute difference in Germany and France is not immediately explainable. Among the possible explanations, the accounting for space heating seems to be a likely candidate, due to generally scarce data availability in industry regarding floor area as well as specific energy consumption.

The temperature shares used in Naegler et al. 2016, Pardo et al. 2013 and by us are compared in Figure 10. While for most subsectors, the temperature distribution shows a similar pattern, there is the general trend that our process-based approach shows lower demand below 100 °C than the subsector-based approaches. Most characteristic is high temperature energy demand in minerals, and metallic industries (blast furnace, cement kiln, melting furnaces), medium temperature demand in paper and printing (steam for paper production and drying) and low temperature demand in the food subsector. It should also be noted, that Figure 10 shows a representation, weighted by production, of our approach. So the temperature distribution is different in individual countries, based on their economic structure both within subsectors and as a whole.

Our approach of combining bottom-up data on process level and top-down energy balance to include temperature and application as new dimensions shows promising results. Compared to individual national energy balances, our approach has the main advantage that results are comparable, because we use a coherent methodology across all countries. Our approach combines the technological explicit knowledge of processes and their individual properties with real production values and available energy balances (both Eurostat and

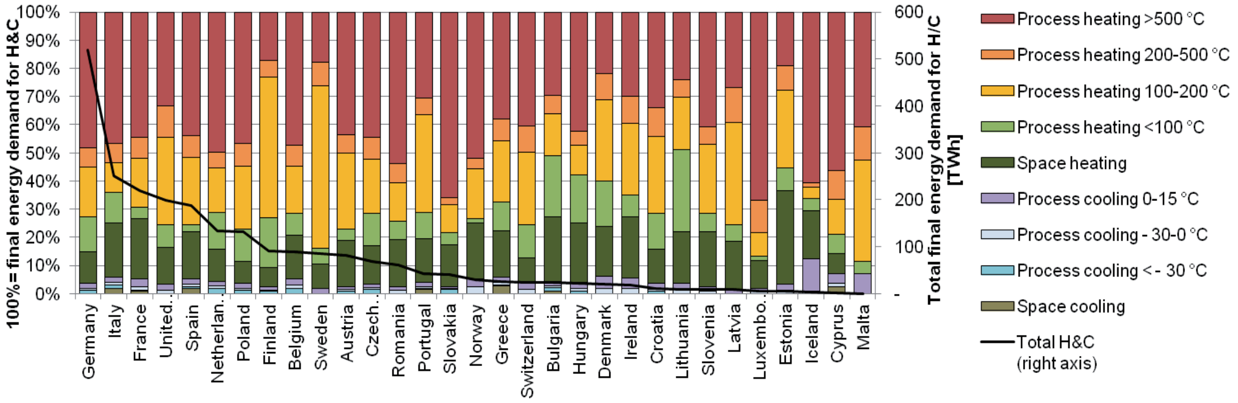

Figure 7. Temperature share and final energy demand for heating and cooling by country for the EU28+3.

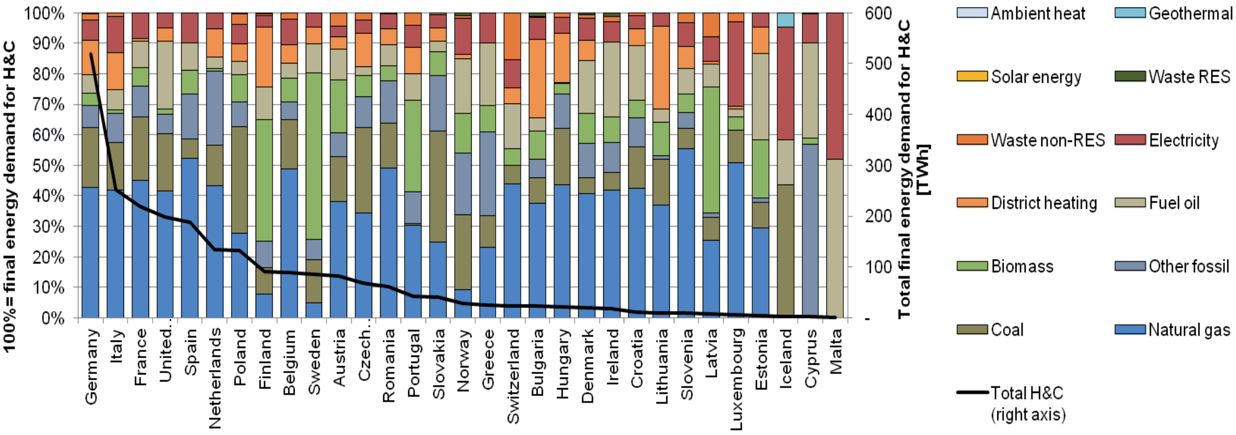

Figure 8. Energy carrier share and final energy demand by country for the EU28+3.

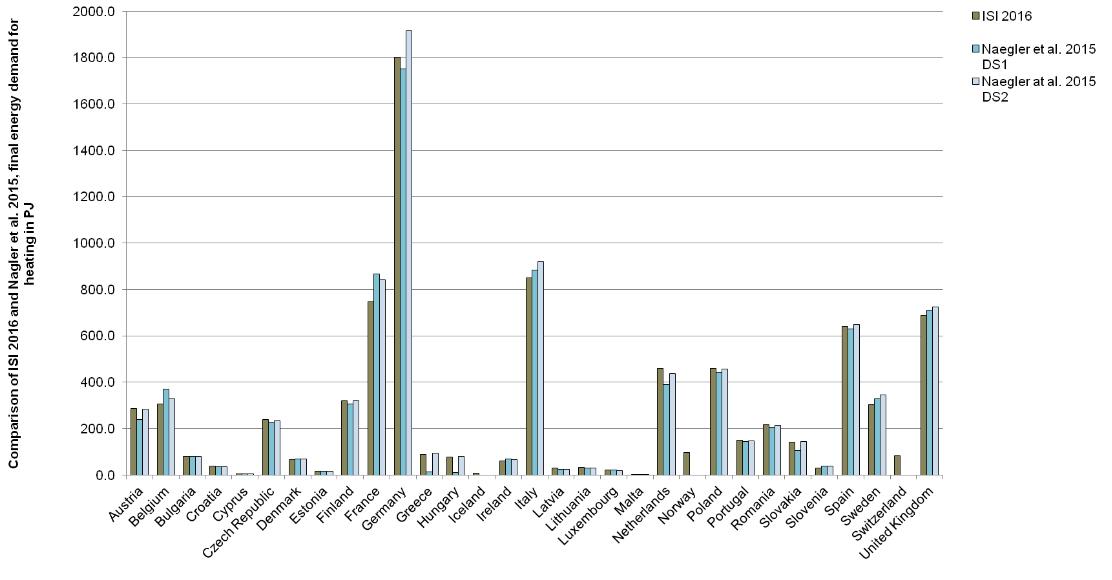

Figure 9. Final energy demand for heating, comparison of ISI 2016 and Naegler et al. 2015.

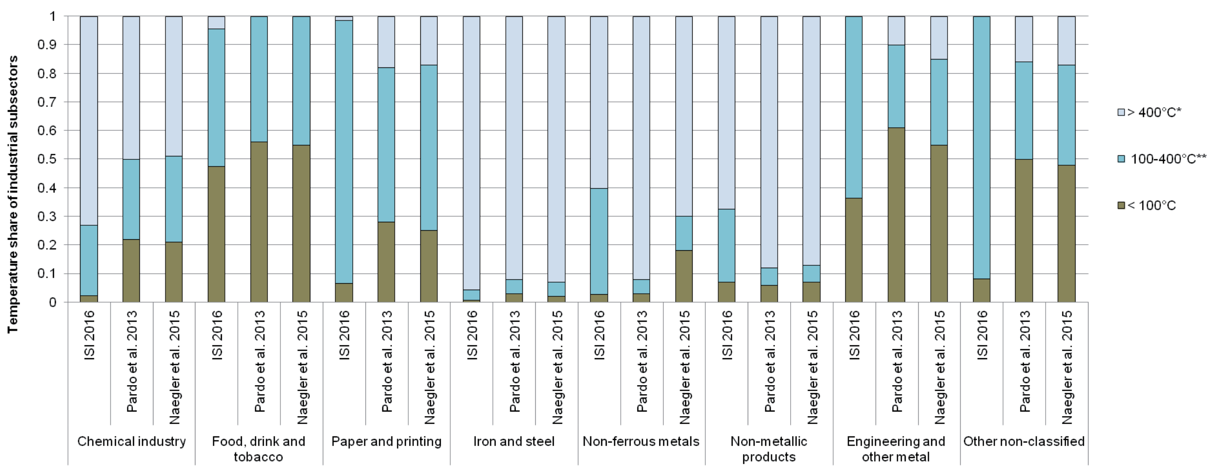

*Figure 10. Temperature share assumptions by subsector: Comparison of Pardo et al. 2013, Naegler et al. 2015 and ISI 2016; ISI 2016: weighted average of processes in respective subsector, * ISI 2016: >500 °C, ** ISI 2016: 100–500 °C.*

national). The general approach, that specific energy demand times production equals total energy demand is immediately evident, and the well maintained database of processes and activity ensures high bottom-up coverage of many big and most smaller countries. The approach has, however, several weaknesses, that should be addressed.

It relies on the availability of production data on a process level, which is not always satisfying, especially for smaller countries or those with an unusual industrial structure. Also, analysis of the bottom-up coverage shows that in some sectors (like chemicals) process structure can be very diverse, limiting the achievable share of the bottom-up modelled industry. For example, as of today, the ECHA (2016) lists over 15,000 products related to the chemical industry, of which 43 are produced in tonnages over 10 Mt per year. The focus on energy-intensive industries, while necessarily neglecting others, of FORECAST is thus both strength and weakness.

Detailed knowledge about processes and their key indicators (specific energy demand, temperature profile, applicable energy carriers) is necessary to achieve plausible results. Therefore, specialised and small processes, which lack thorough research due to their relatively low importance in terms of absolute energy demand, are problematic. Still, it remains questionable whether increased effort is justified in general. Fleiter et al. (2013) found that, for Germany, the included processes cover up to 86 % of the fuel demand, with the biggest 20 already covering around 75 %. Further research therefore should be focused on singular processes that are identified as relevant for special countries of interest.

Shortcomings in any of these fields lead to a significant loss of precision, as energy demand that is not covered in the bottom-up approach is treated on an aggregated subsector level. This means that smaller processes that are not modelled in detail tend to be marginalized, even if they may possess increased relevance in some countries with an unusual economic structure. This puts emphasis on the temperature distribution aggregated to subsector level, as it can alleviate this drawback when well considered.

The basic assumption that process equals process, while being a mostly sensible one in general, ignores some differences in energy efficiency or other process characteristics that exist among countries with technological disparities. Further research how technological differences among countries contribute to their processes' efficiency and specific energy demand, possibly linking it to easier accessible data of a higher aggregation level, seems necessary.

In general, the quality of the results depends heavily on the bottom-up covered share of total industrial energy demand, so not only process specific data but available production figures have the most important influence.

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