Generating energy carrier specific space heating and hot water load profiles at NUTS-3-level in Europe

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Abstract:

The electrification of heating applications represents one significant component in the decarbonisation of private households [1]. The spatial distribution of diverse kinds of energy carriers used for heating applications within a country (heating structure) is usually not homogeneous. Population density and climatic conditions are influencing factors determining the type of energy carrier and the used heating system in a region. Hence, the selective substitution of fossil-fired heating systems by electrically fired ones induces spatially varying changes in the electrical load. Accordingly, the key motivation for this paper is to develop a methodology to generate spatially differentiated electrical load profiles by using heating structures.

A top-down approach is used to model space heating and hot water load profiles in the spatial resolution of NUTS-3-regions. The study focuses on the German energy system. Hence, in the context of the European electricity market coupling the 14 current and future electrical neighbouring countries of Germany and Austria as well as Austria itself are of major interest.

For these 15 countries, national energy balances are modified to generate application balances in which the yearly final energy consumption is determined. The part of final energy needed for space heating and hot water split up into energy carriers is allocated to the NUTS-3-regions by using the distribution of heating systems. Variations in climatic conditions are taken into account by degree day numbers at NUTS-3-level. The spatial distribution of heating systems by energy carriers is provided by the national offices for statistics. If the data quality is lower, regional final energy consumption by energy carrier is used. Thereby additional applications (lighting, cooking, ...) have to be subtracted from the data to derive the heating structure for space heating and hot water. However, these methods cannot be applied to all countries due to variations in data availability and quality, making individual methods necessary. The annual final energy consumption for space heating and hot water of each NUTS-3-region is converted into daily resolved data using the degree day numbers, whereby no seasonal effect is assumed for hot water consumption. Using temperature-dependent standard gas load profiles the daily quantities of space heating and hot water demand are transformed into hourly load profiles. Finally it is shown how a change in energy carrier towards electricity based energy carrier impacts peak load and load distribution on NUTS-3-level for a chosen scenario.

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Keywords: electrification, policy measures, private households, energy balance

1 Motivation

The project eXtremOS (XOS) investigates the value of flexibility in the context of European electricity market coupling and extreme technological, regulatory and social developments. Within XOS disruptive impacts on the energy system by e.g. radical regulatory measures are investigated. One regulatory measurement taken in Denmark in recent years was banning the installation of oil-fired boilers and natural gas heating in new buildings from 1st of January 2013. Furthermore, since 2016 the installation of new oil-fired boilers in existing building is banned as well if district heating is available in these areas. To be able to model the impacts of such developments one of the first aims of XOS is to develop a profound database. The purpose of this paper is to publish the approach, which is used to generate a spatial and temporal resolution of energy carrier specific demand for space heating and hot water on NUTS-3-level of private households (PHH). Spatial resolution allows to investigate the impacts of changing demands of energy carriers from a grid perspective whereas temporal resolution is of interest if considering also changes in types of energy carriers, e.g. electricity. To this end, the integrated simulation model for unit dispatch and expansion with regionalization (ISAaR) will be used in XOS.

2 Methodological approach

Figure ***1*** gives an overview on the methodological approach for the spatial and temporal distribution of final energy consumption (FEC) of space heating and hot water in XOS so far. It consists of the three major steps: (1) Application oriented energy balance[1]; (2) Spatial distribution; (3) Temporal distribution. These three steps are described in more detail in the following.

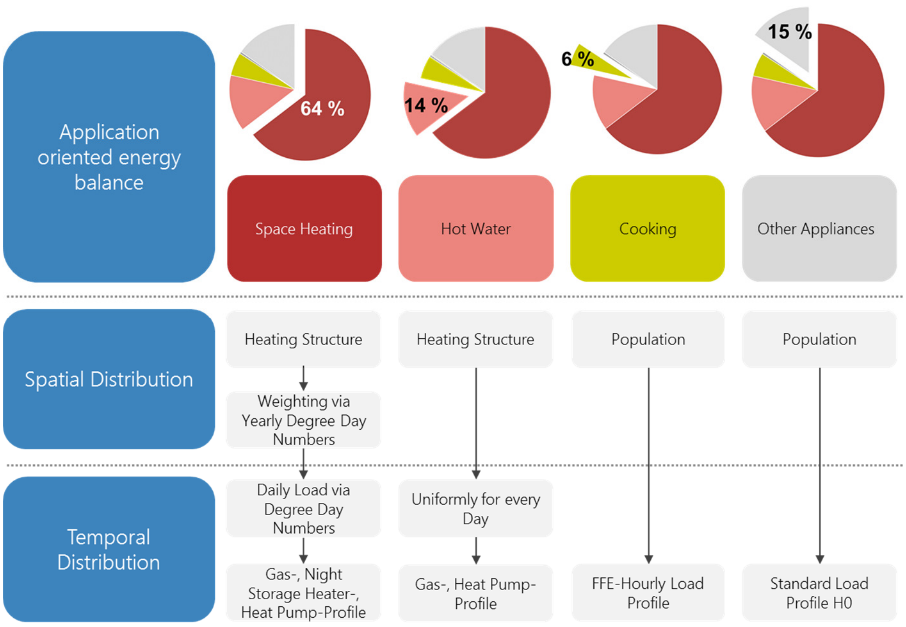

Figure 1: Overview on the methodological approach

[1] The sum of all appliances is 99 % instead of 100 % in this illustration. This is due to rounding errors.

2.1 Application oriented energy balance

As a first step application oriented energy balances are derived. Starting point are the energy balances for every country. Since 1990 they are published yearly for EU-28, as well as for a couple of partner countries uniformly [2] and contain information on the split of energy carrier for every single final energy sector. Within EU-28 about 27 % of FEC can be attributed to PHH. These however, only account for 23 % of GHG-emissions in the energy sector. In order to categorize the applications in PHH [3] can be used, which defines the application classes with respect to “space heating”, “space cooling”, “water heating”, “cooking”, “light and appliances” and “other end uses”. With 64 % the major share of FEC is attributed to space heating while the second largest share is attributed to water heating Cooking accounts for the lowest share (~6 %) of heat appliances. Cooling is of minor relevance (~0,5 %). Other appliances account for 16 % of FEC. However, this publication only focusses on “space heating” and “hot water” in the following.

2.2 Spatial distribution

As shown in *Figure **1*** a specific approach for the regional distribution is performed depending on the application. For cooking and other appliances only the population is used as distribution criteria. Whereas for space heating and hot water the approach is based on the heating structure. Additionally, a weighting by heating degree days is applied in case of space heating. The methodological approach to deduce the spatial distribution of energy carrier specific FEC is shown in *Figure **2***.

There are four input datasets consisting of temperature data, application oriented energy balance, heating structure and population statistics. Based on this data the two outputs “yearly FEC per energy carrier on NUTS-3-level for space heating” and “yearly FEC per energy carrier on NUTS-3-level for hot water” are calculated. The calculation itself contains three steps.

(1) In order to distribute the total FEC of each energy carrier the heating structure is transformed into a population weighted heating structure (PWHS). The heating structure (HS) itself reflects the share of each energy carrier used for heating within every NUTS-3-region. Whereas the PWHS reflects the share of every energy carrier used for heating among all NUTS-3-regions. Hence, the sum over all NUTS-3-regions equals one per energy carrier.
(2) The FEC per application and energy carrier on NUTS-3-level is calculated by multiplying the PWHS with the FEC on NUTS-0-level for each energy carrier.
(3) As climate conditions are the major driver for space heating a weighting of the FEC for space heating via year degree day numbers (c.f. section 2.2.1) on NUTS-3-level is performed.

Subsequently the preparations of the input datasets temperature and heating structure are described. The application oriented energy balance is already described in 2.1 and data used for population statistics is taken from [4].

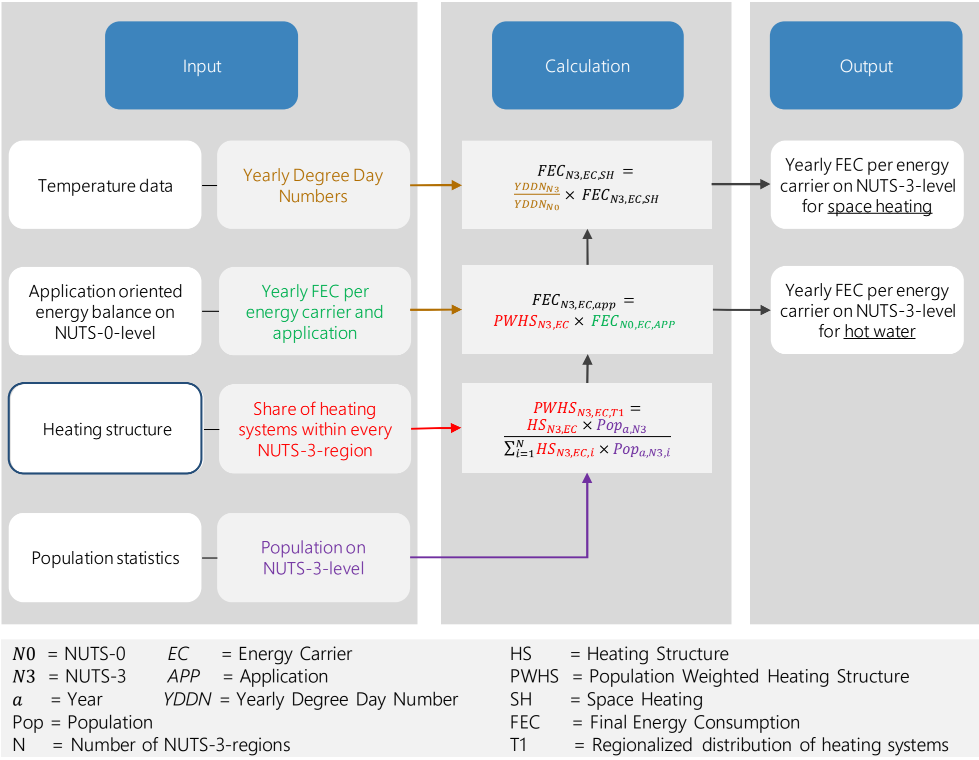

Figure 2: Methodological approach to deduce energy carrier specific FEC for space heating and hot water

2.2.1 Temperature data

The main factor to determine the demand for space heating is the temperature. Temperature data is taken at a height of 2 m in hourly resolution from the widely used COSMO-EU weather model at a spatial resolution of 7 km x 7 km. For each NUTS-3-regions the most populated city is used as reference point.

Nonetheless, as the inertia of the building mass is not neglectable this data has to be processed further. The degree day numbers (DDN) are calculated as described in VDI 3807 with a small adaptation. Instead of using the average daily temperature the daily equivalence temperature (DAT) is used to account for the temperature inertia of the building as described in [5]. The sum of DDN of one year equals the yearly degree day number (YDDN). The YDDN is calculated for each NUTS-3-region as well as for NUTS-0-level. The latter is defined as the average of all YDDN for the NUTS-3-regions. Apart from the outdoor temperature, further parameters necessary for the calculation of the YDDN are the indoor temperature and the heating threshold temperature. They are set to 20°C and 15°C respectively for all countries due to the lack of country specific data.

2.2.2 Heating structure

With more than 60 % of FEC in PHH the main focus lies on the identification of the energy carrier used for space heating. Hence, the HS reflects the share of heating systems by energy carrier used for space heating within every NUTS-3-region. For reasons of simplification it is assumed that hot water is supplied by the same energy carrier, although there are also cases where its provided by other technologies. A different approach would be to assume a linear distribution of the FEC for hot water via population, however, this is assumed to be more inaccurate.

Raw datasets are often provided by the national statistical offices or are published with census data. The list of identified datasets for 15 countries is given in *Table 1*. Once identified these datasets undergo a preprocessing. Depending on the country their spatial resolution varies. Aim is to gain a spatially resolved share of energy carriers on final energy consumption for heating appliances on NUTS-3-level. Thus, if the spatial resolution of the identified dataset is less than NUTS-3-level a population based distribution of heating structures down to NUTS-3-level is conducted. In a second step it is necessary to verify the applicability and the completeness of the datasets. If data is not available for some regions for a specific year data from other years is interpolated. Energy carriers that are not contained within the dataset, though known to be used from the application oriented energy balance, are distributed uniformly according to the population.

After this pre-processing there are two categories of datasets, which are processed differently. Type one contains the number of heating systems by energy carrier as share or in absolute values.

Data of category two contains information on the FEC by energy carrier but without indication on how much of the FEC is actually used for heating appliances. These datasets do not have to be processed according to *Figure 1*. In this case the national application balances were used to extract the share of energy carriers used for other appliances than heating, which is especially important for electricity due to the fact that electric heating has low share compared to other electrical appliances. FEC for hot water per NUTS-3-level is calculated according to the share of population w.r.t. the FEC for hot water on NUTS-0-level, the residual is the FEC for space heating.

Table 1: Level of detail and type of processing for the heating structure in each country

Country	Level of detail	Category of processing	Source
Austria	NUTS-3	1	[6]
Belgium	NUTS-1	1	[7]
Czech Republic	NUTS-3	1	[8]
Denmark	NUTS-3	1	[9]
France	LAU-1	1	[10]
Hungary	NUTS-3	2	[11]
Italy	NUTS-2	1	[12]
Netherlands	LAU-2	2	[13]
Norway	NUTS-2	2	[14]
Poland	NUTS-3	1	[15]
Sweden	NUTS-3	2	[16]
Switzerland	NUTS-3	1	[17]
Slowakia	NUTS-0	1	[18]
Slowenia	NUTS-3	1	[19]
United Kingdom	LAU-1	2	[20]

Figure 3 shows the relative distribution of heating systems contained in the Swiss data source. It becomes obvious that the share of the different heating systems varies significantly between the 26 NUTS-3-regions. This shows that such data is of great value to investigate the impact of energy carrier specific policy measures on a local scale.

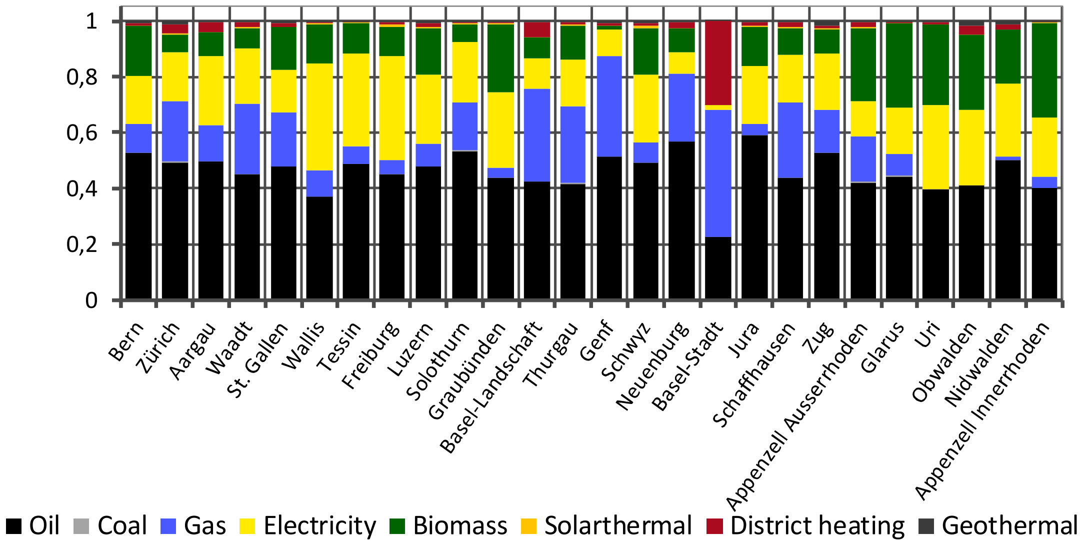

Figure 3: Share of heating systems in Switzerland by energy carrier and NUTS-3-region, data from [17]

2.2.3 Shortcomings

Apart from outside temperature and heating structure there are further drivers influencing heat demand. However, the following factors are neglected so far. For example, air exchange rate or assumed room temperature are user behavior related factors. Furthermore, weather related factors are solar irradiation, cloud cover and wind speed which are not taken into account. On top there are building related aspects like living area, window sizes and other ones which determine the degree of insulation. In particular, average living area and the degree of insulation vary between regions and countries. Nevertheless, the latter influences the heat threshold temperature, which is used in calculating the FEC (c.f. sec. 2.2.1). Heat threshold temperature data varies between countries. For Switzerland there are sources which assume it to be 12°C [21]. For Germany there are sources that state 15°C [22], [23] is the correct temperature. Depending on the study values within Europe reach up to 15.5°C [24]. However, due to the fact that this information is not available for every country it is assumed to be 15°C in every case.

2.3 Temporal distribution

In the end, hourly load profiles can be elaborated based on e.g. [25] for gas, [5] for night storage heaters or [5] for heat pumps. *Figure **4*** shows the hourly share of daily demand for space heating and hot water in temperature intervals according to the used gas load profiles. These can be interpreted as the course of the heat demand in a first order approach. Hence, the gas load profile might be used as an approximation for direct electrical heating if no storage is assumed.

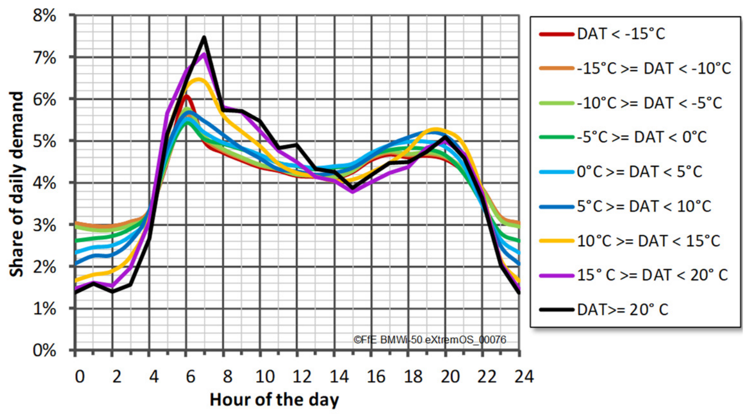

Figure 4: Hourly share of daily demand for space heating and hot water in temperature intervals [25], own illustration

The available profiles allow to create electrical load profile for different technologies. To deduce the hourly load curves the difference in efficiency of the employed technology compared to the substituted one has to be taken into account. This is done by scaling the FEC.

3 Applications for the derived data

About 80 % of final energy in private households is resolved hourly for the NUTS-3-regions. Spatial characteristics concerning the use of energy carriers and the resulting loads, depending on the outdoor temperature can be derived from the model.

Figure ***5*** shows the distribution of electrical heating systems in France. There is a higher share of electrical heating systems in the south and south-west, declining by looking to the interior of the country.

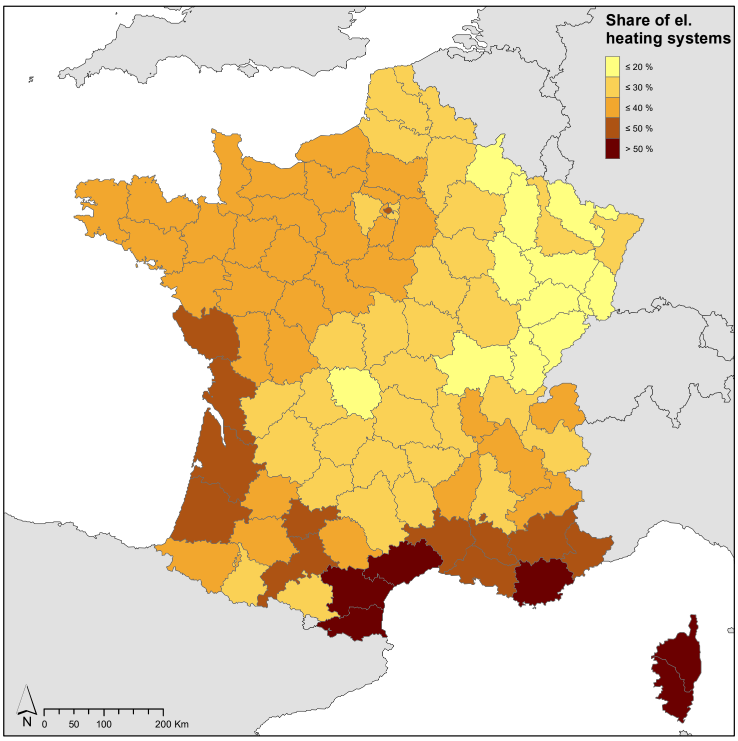

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Figure 5: Share of electrical heating systems in each NUTS-3-region in France [2]

Considerable differences in the heating structure within a country are shown by the load profiles in *Figure* ***6*** (exemplary shown for Switzerland). In Basel-Stadt district heating and gas are primarily used to provide heat. The share of electrical and oil-fired heating systems is lowest on state average, whereas in Ticino their share is substantially higher. Base load corresponds to the provision of hot water while the volatile share of the annual load curve is attributable to the temperature-dependent space heating. The derived load curve split into energy carriers can be transformed into an electrical load (e.g. by using heat pumps as in [3]) to investigate effects of energy carrier specific policy measures. This data is needed for spatially resolved energy system models.

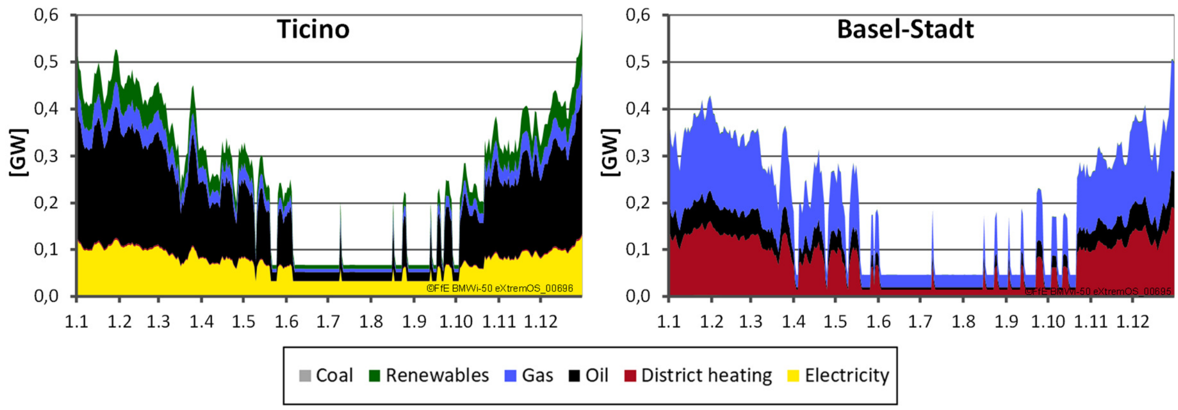

Figure 6: Space heating and hot water load curves of two Swiss NUTS-3-regions for 2014

3.1 Scenario

The main purpose of the chosen scenario is to illustrate the application of the derived model, hence it is a simple and generic one. The developments presented do not correspond to any forecasts of the authors. It is assumed that no more gas and oil-fired heating systems in private households exist. They are substituted by electrical heating systems. Oil-fired heating systems are substituted by heat pumps as oil-fired heating systems are supposed to be mainly implemented in less densely populated areas with enough space for the implementation of efficient geothermal systems. On the other hand, private households with a gas connection tend to have less space, which is why it is assumed that the gas-fired heating systems will be replaced by direct electrical heating. Furthermore it is assumed that oil-fired heating systems have an annual efficiency of 0.9 and gas systems 0.95. A coefficient of performance for heat pumps of 2.8 and for direct electrical heating of 1 is assumed.

To allow for a deeper understanding of the spatial differences in the share of oil and gas fired heating systems as well as its significance, the regional distribution of these energy carriers is shown in the following. The effects of the electrification is discussed in section 3.2.

Differences in the regional shares of both energy carriers are investigated in detail by using indices which are calculated by formula (1).

$$I_{enery\ carrier,\ NUTS-3} = \frac{Q_{enery\ carrier,\ NUTS-3}}{\{NUTS\text{-}3\ \in NUTS\text{-}0\ |\ \overline{Q}_{NUTS-3}\}} \qquad (1)$$

Q: Consumption of heat supplies

$\overline{Q}$: Average consumption of heat applications

The consumption of the energy carrier used for space heating and hot water per NUTS-3-region is normalized to the average consumption of all energy carriers for heat applications in PHH of each country. Due to this normalization, the share of the considered energy carrier with respect to the total energy used of heating applications is contained within the index. The comparison among countries with the chosen index is possible, as well. This is achieved by the normalization of Q to the number of NUTS-3-regions. The indices for both energy carriers per NUTS-3-region are compared in the scatterplots for selected countries (Figure 7). The bubble size represents the whole consumption of heat applications per NUTS-3-regions. In France, in total and related to other energy carriers less oil and gas are consumed compared to United Kingdom and Germany. This is indicated by the accumulation of the bubbles in the lower left corner. More gas than oil is applied in NUTS-3-regions in France with higher consumption. In the United Kingdom gas is used in much more NUTS-3-regions than oil, but oil is applied in some NUTS-3-regions with quite high consumption. Italy is quite similar to the United Kingdom but does not have NUTS-3-regions, in which oil is utilized. In Germany the share of oil and gas is quite balanced. Some NUTS-3-regions contain a bit more oil than gas fired heating systems and the other way around.

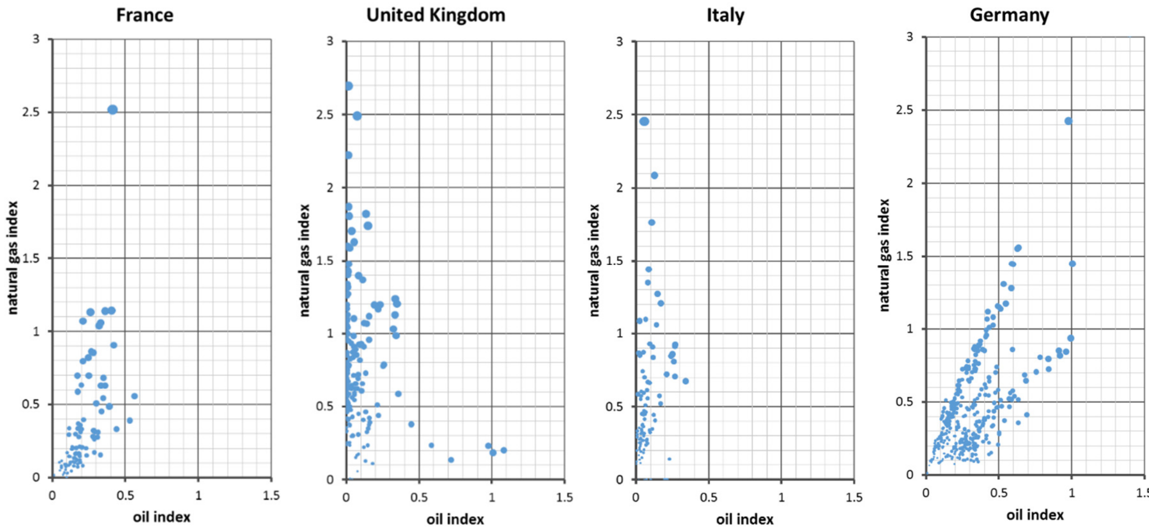

Figure 7: Comparison of oil and gas indices for the NUTS-3-regions per country

The scatterplots show the varying share of oil and gas in the NUTS-3-regions. This information can no longer be clearly identified in a map, but an evaluation of the spatial differences is possible (Figure 8). For example Northern Ireland is characterised by more oil than by gas whereas it is the other way around in Great Britain.

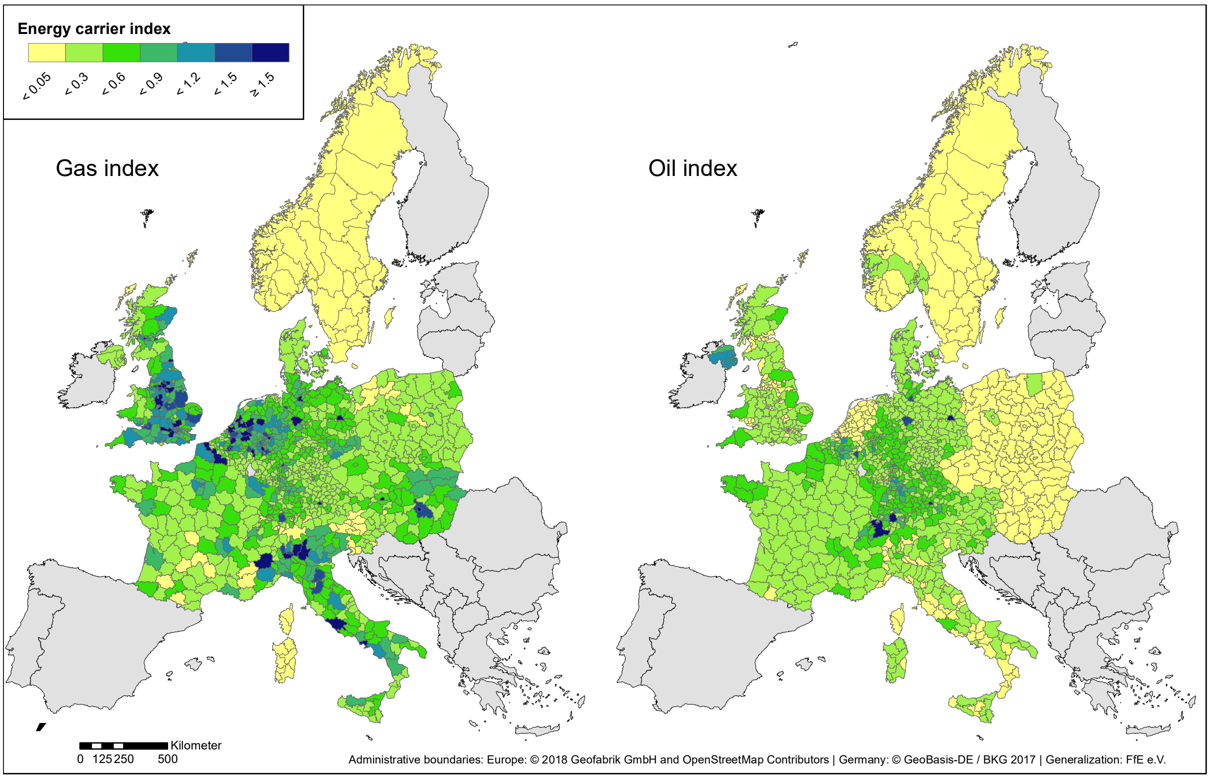

Figure 8: Energy carrier index for oil and gas

These evaluations show that the derived model is able to show differences in the energy mix for heat applications in PHH at the level of the NUTS-3–regions. Hence it is suitable to investigate the effects of regulatory measurements on specific energy carriers with respect to their spatially different implications.

3.2 Evaluation

The increase in electricity consumption depends on the amount of oil and gas in the respective country and is implicitly reflected in the energy carrier index. More interesting, however, is the change of peak load and its regional differences within the countries in the case of substitution. The impact of the substitution the peak load does not only depend on the ratio of electricity consumption to gas or oil consumption but also on the temperature time series as application-specific load profiles per NUTS-3-region are used (section 2.3).

The change of peak load of PHH after substitution in relation to the current peak load is shown in Figure 9. The peak load of PHH increases up to more than 600 % in some NUTS-3-regions in this scenario. Obviously, countries with low consumption of Gas and Oil like Norway and Sweden have a small change of the peak load. In countries with a relatively low ratio of electricity consumption to gas and oil consumption such as France an Poland, the change of peak load is also relatively low. The greater the share between electricity consumption and oil or gas consumption, the more the change of peak load increases, as in the UK, Germany, the Netherlands, Hungary and Italy.

However, it is noticeable that the changes in peak loads can vary considerably between countries with a similar ratio of electricity consumption before and after substitution. For example, in many regions of Italy the value reaches over 600 %, whereas in the UK they reach a maximum of 350 %. This is due to the temperature-dependent gas load profiles used in the calculation of peak loads. Compared to Italy, the United Kingdom has more heating days per year. As a result of the applied methodology heat demand is spread over more days. Thus, the same gas consumption in Italy leads to higher peak loads.

In addition to cross-country statements, it is possible to make statements about the regional distribution within a country. For example in Italy the change of peak load rises up to more than 600 %, whereas in areas on the Adriatic and on Sicily only an increase of 300 % to 400 % can be recorded.

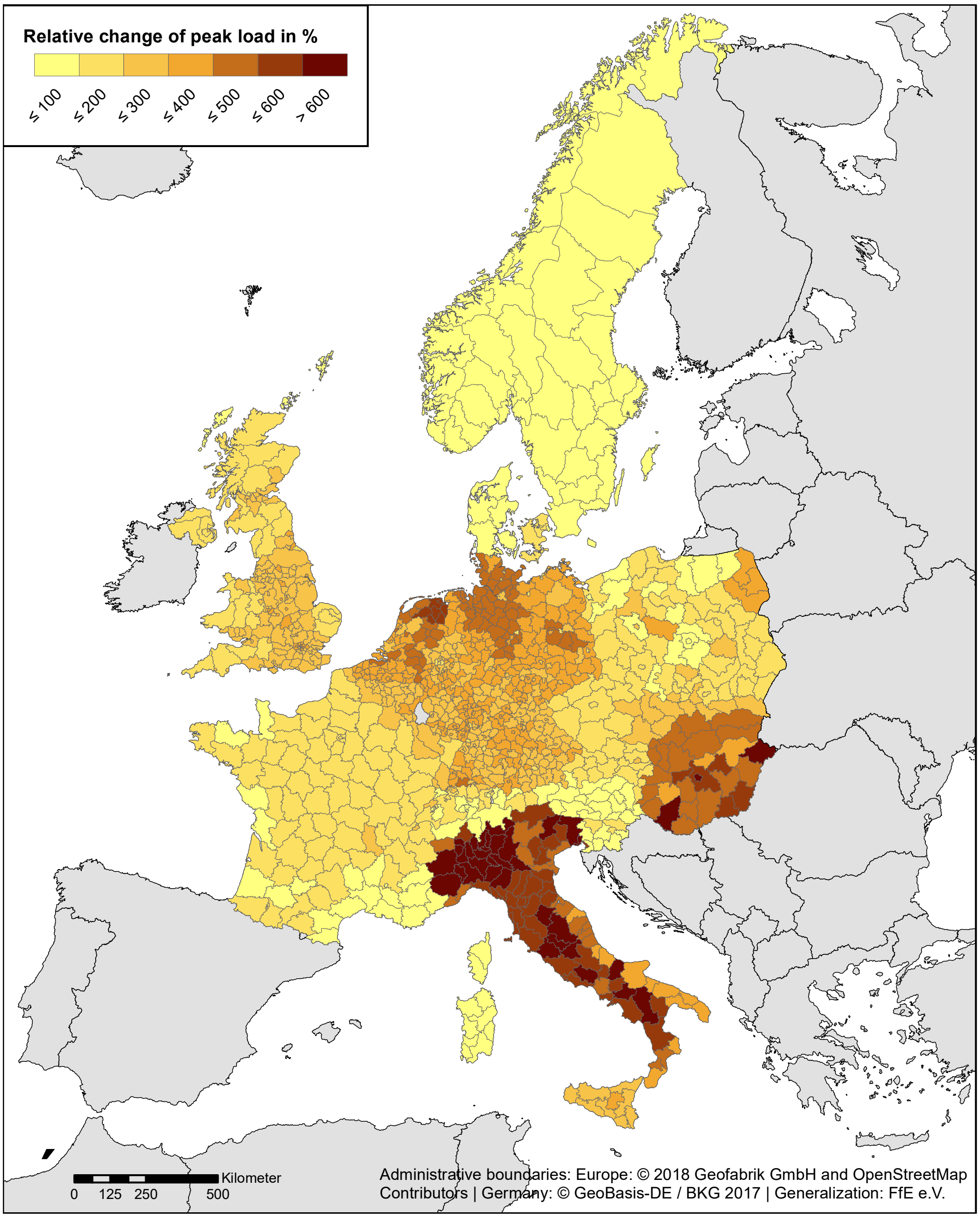

Figure 9: Relative change of peak load of private households on NUTS-3-level

In addition to the relative change of peak load, the increase of the peak load and the increase of the consumption is compared (Figure 10). The peak load increases faster than the consumption. For example at an increase of the consumption of 200 % the increase of the peak load varies from 200 % to 500 %.

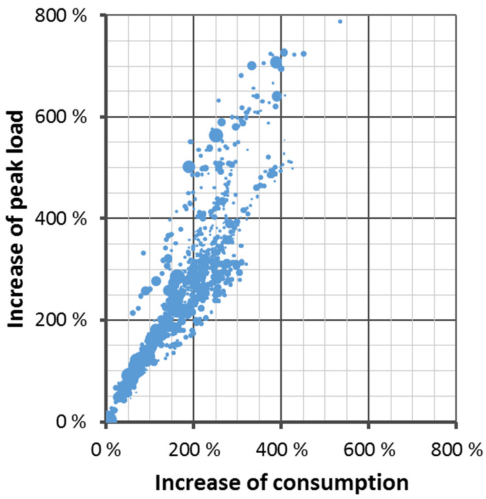

Figure 10: Comparison between increasing consumption and peak load in all NUTS-3-regions

These evaluations show the benefit of the derived model as they show the significance to investigate a substitution scenario on a spatial level, which is lower than the country level. The NUTS-3-level has proven to be an appropriate one in such a scenario.

4 Conclusion and Outlook

Apart from renovation, the most important measure for the decarbonisation of the private household sector is the electrification of heating applications. As different energy carriers are used for heating applications so far, their electrification may depend on the fuel being used. For this reason, the aim of this paper is to develop a methodology to generate spatially differentiated electrical load profiles for heating applications in private households depending on the energy carrier used today.

The methodology is based on a top-down approach in which the final energy consumption of each heating application is spatially distributed according to the heating structure – the share of each energy carrier used for space heating within every NUTS-3-region within a country. In addition, degree day numbers are used to indicate varying climate conditions and to convert the annual final consumption per NUTS-3-region into daily resolved data whereby no seasonal effect is assumed for hot water consumption. Hourly load profiles for space heating and hot water are generated by using temperature–dependent standard gas and in case of electricity technology-dependent load profiles. The main result is data on spatially and technologically differentiated load profiles depending on the applications space hating and hot water.

One possible usage of the data, generated by the presented methodology, is discussed in a substitution scenario: the energy carriers oil and gas are substituted by heat pumps and direct electrical heating. The substitution scenario allows for a high level investigation of the impact of electrification measures on the electrical transmission grid. The analyses of the scenario show strong spatial differences in the peak load of private households within a country. This proves that a resolution at NUTS-3-level is necessary for energy system analysis, which consider the electrical transmission grid.

As next steps the model can be refined with more country specific input data. Furthermore, implications of renovation and demography can be implemented into the model. Apart from the view on private households similar models will be developed for other sectors.

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