Temporal and Spatial Resolution of Greenhouse Gas Emissions in Europe

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EXECUTIVE SUMMARY
• 1 Introduction

This report presents proposals of methods for the spatial and temporal disaggregation of anthropogenic greenhouse gas emissions in Europe. It takes into consideration the results of the workshop on this topic that was held in Stuttgart, Germany, on June, 26-27 2003 in the frame of the European Concerted Action CarboEurope GHG.

A lot of work in the field of spatial and temporal emission resolution has already been conducted for other trace gases, e.g. in the EUROTRAC subproject GENEMIS, or in the frame of the German Tropospheric Research Programme, but yet there has not been much work done in the spatial or temporal resolution of greenhouse gas emissions. The status quo of greenhouse gas emission resolution corresponds to the annual national communications of parties to the UNFCC. According to modeller specifications, any resolution better than annual and national would be helpful but the aim is to obtain hourly emission data on a 10 km * 10 km grid if possible.

In most cases, the disaggregation methodology developed for ‘classic’ air pollutants (NO\textsubscript{x}, NMVOC, SO\textsubscript{2}, CO etc.) can be applied for greenhouse gases as well because they depend on the same activities of emission sources. However, in some cases greenhouse gas emissions follow distinct time curves. Concerning agriculture, for example, studies about the temporal distribution of NH\textsubscript{3} emissions have been conducted, but those time curves are not necessarily applicable for emissions of CH\textsubscript{4} or CO\textsubscript{2}. In order to account for greenhouse gas budgets, the developed methodology needs to be improved and adapted to be applicable to GHG emissions.

Adaptation is also necessary regarding classification of emission source groups. Within GENEMIS, emission sources were grouped with respect to CORINAIR “Selected Nomenclature for Air Pollution”. National greenhouse gas emission inventories are in most cases based on the International Panel on Climate Change (IPCC) guidelines and emission sources are thus categorised pursuant to the IPCC Common Reporting Format (CRF) since 2000. Correlation between SNAP and CRF was established during the development of the Nomenclature For Reporting (NFR) by UNECE Task Force on Emission Inventories and Projections and can be used to allocate greenhouse gas emissions to SNAP or NRF sectors. Based on the approaches developed in the context of GENEMIS, methods of spatial and temporal disaggregation are proposed for emission source groups comprising sources with similar temporal activity:

- Public Power
- Refineries, extraction and distribution of fossil fuels
- Industry
- Small consumer combustion
- Road traffic
- Other mobile sources
- Waste
- Agriculture

The main focus in this report will be on temporal disaggregation, since the need for improvements in this field is much higher than the need to improve methods for spatial disaggregation, which are already well developed.

In this report, the major greenhouse gases CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O of anthropogenic origin are considered. Biogenic emissions are covered by another CarboEurope GHG Workpackage. Concerning agriculture, this brought up the question of competence. The following arrangement was made: all emissions that occur before the application of manure or fertilizer on agricultural land are considered to be anthropogenic and are addressed in this report. Emissions from Agriculture were discussed in a separate group during the workshop and are addressed in a separate chapter in this report, too.


2.1 Public Power and District Heat

Energy industries account for about one third of total CO₂ emissions in the European Community (Greenhouse Gas Inventory Database in http://ghg.unfccc.int/). Therefore, their temporal patterns are of great importance, too, and should best be ascertained by direct measurement. Measured data are theoretically available since the Large Combustion Directive LCPD (2001/80/EC) specifies the duty for operators of large combustion plants with a nominal capacity ≥ 300 MW to perform continuous emission measurements. Practically, such data giving information about temporal patterns are mostly kept confidential by energy producers due to issues of competitiveness, especially since the deregulation of the European electricity markets has taken place. Therefore, models describing typical variations in energy demand are used to derive temporal variations of emissions from power plants.

Emissions patterns can be deduced from the temporal variations of energy demand if proportionality between emissions, fuel use and electricity or heat production and furthermore proportionality between production and demand per time unit is assumed. Proportionality between electricity and heat production and demand can be assumed at any time because neither electricity nor heat can be stored efficiently. To allocate the simulated production to particular plants, economic models can be used based on information about the types of power plants (fuels, full load operation times, plant type: power plants (PP), heat plants (HP) and combined heat and power plants (CHP)) to distribute grid load and heat demand to a known power plant pool. Two problems with taking this approach were generated or increased with the liberalisation of electricity markets:

1. No clearly defined power supply area (closed area that receives its energy by one power plant pool) can be allocated to one power plant pool, as the European power grid makes it possible to generate electricity on demand anywhere where production prices are lowest.
2. Data availability from power supply companies has decreased even more due to more pronounced competition.

Despite the difficulty of allocating demand based grid loads to particular power plants, their temporal behaviour must still be approached from demand side because even less data is available from power supply companies.

Within the EUROTRAC subproject GENEMIS, temporal emission patterns of European public power and heat plants have been simulated based on annual emission data from CORINAIR and LOTOS emission inventories. A method for calculation of emissions from public power and heat supply in Europe with high temporal resolution was developed and described in (Adolph, 1997). It can be used to calculate hourly emissions of greenhouse gases from power and heat plants in Europe based on currently available annual and monthly emission data. Emissions are disaggregated gradually for months, days and hours. Monthly disaggregation is based on monthly energy statistics available from EUROSTAT (EUROSTAT, 2003) and other international and national statistics and on temperature variations. To calculate variations from day to day, temperature influence and the influence of weekdays are taken into account. Daily emissions are resolved to hourly emissions using typical heat and electricity demand time-variation curves. Chapter 2.1.1 is a summary and interpretation of the method described in (Adolph, 1997).
2.1.1 “Calculation of emissions from public power and heat supply in Europe with high temporal resolution”

Energy demand is the most important command variable for power plant operation. Production and demand must be kept in equilibrium because storage of electricity and district heat is not practicable. As demand of consumers can hardly be influenced, production must constantly be adjusted to demand variations. The energy supply companies determine how their plants are operated to satisfy demand. Different factors influence energy demand and production. The main factors influencing Energy demand are

- Season (linked to meteorological factors via temperature)
- Working times (regional and sectoral differences)
- Types of consumers (private, commercial, industrial)
- Meteorological factors (temperature, daylight hours)

Information which can be used to derive temporal variations of energy demand are typically available on national level. Even before the electricity market liberalisation occurred, collecting information about energy demand in specific energy supply areas would not have been practicable. Therefore, each country was treated as one supply area with a homogeneous demand structure. Concerning electricity production, this simplification seemed acceptable as in an integrated network regional differences are compensated. Today, the whole European electricity grid would basically have to be regarded as one integrated network because of the liberalisation of the market. However, taking into account that not only economic considerations determine electricity supply but as well issues such as security of supply and self-reliance, the national approach can still be assumed to be valid.

Energy production for demand satisfaction depends mostly on energy demand, but optimise the use of their production capacities, energy supply companies also have to consider

- Fuel types
- Efficiency of plants
- Composition of power plant pools (shares of PP, HP, CHP)
- Amount of rainfall (directly influencing power production in run-of-river plants and indirectly influencing operation of power plants using river water for cooling purposes).

When modelling the operation of a power plant pool, data characterising each plant must be available. Emission inventories only contain information on fossil fuel power and heat plants. Information on other plants (hydroelectric PP and nuclear PP and others) must be provided in addition. For fossil fuel power and heat plants, information on fuel type, type of plant (PP, HP, CHP), fuel consumption, energy production, full load operation hours per annum and the capacity of the plant should be given in emission inventories. It is not feasible to treat each plant individually, hence plants with similar temporal activity are categorised using specification data from emission inventories and other statistics. As the quality of those specifications can vary from country to country and even from plant to plant, categorisation is mainly based on the information on the plant type (PP/HP/CHP), type of fuel and load type (base/medium/peak load, derived from the full load operation hours per annum).

Characteristic operation diagrams are generated for each category. Emissions are disaggregated gradually for months, days and hours. Monthly, daily and hourly time factors TF can be calculated with
For monthly and daily disaggregation of emissions, the influence of ambient temperature on electricity and heat demand must be taken into account and is therefore described in the following chapter.

The influence of ambient temperature on electricity demand and power plant operation

Correlation between electricity demand and ambient temperature has been analysed in several studies (e.g. (Nitz, 1992) and (Thorn, 1976)). Winter and summertime are treated separately because in winter, electricity demand depends more on ambient temperature. The reason for that is basically the additional energy demand for heating but also an increased energy demand for cooking due to higher need for warm meals when temperatures are lower. Temperature has less influence on electricity demand in summer but the influence increases on very hot days. While in winter electricity demand rises with decreasing temperature, in summer the demand can rise with rising temperatures due to increasing need for warm water for bathroom and shower. The change of sign is assumed to occur at about 15 °C mean daily temperature.

Below 7.5 °C the dependency of electricity demand from ambient temperature \( p_{\text{elec}} \,[\%/°C] \) is calculated based on a study on grid load variations in Hamburg (Nitz, 1992). The calculated relative temperature dependency of 1 %/°C coincides with the results of a Swiss study on temperature and price dependency of electricity demand. It is also in agreement with the experiences of the German Network Association (DVG), the German Association of Electric Works (VDEW) and several other energy supply companies in Germany. Above 7.5 °C temperature dependency is approximated with a third order polynomial with different coefficients for three additional temperature ranges:

\[
p_{\text{elec}}(T) = a_T + b_T \cdot T + c_T \cdot T^2 + d_T \cdot T^3 \quad \text{in } [\%/°C] \text{ for } T > 7.5 \, ^\circ C
\]

where \( T \) - temperature in [°C].

This approach is based on the results of the Hamburg study (Nitz, 1992) and of a study about procedures to predict short- and medium-term daily grid load curves (Thorn, 1976). Temperature ranges and polynomial coefficients are listed in Table 1. Figure 1 shows temperature influence on electricity demand versus ambient temperature.

Table 1: Temperature ranges and polynomial coefficients to represent temperature influence on electricity demand

<table>
<thead>
<tr>
<th></th>
<th>I. ( T \leq 7.5 ^\circ C )</th>
<th>II. ( 7.5 ^\circ C \leq T \leq 12.5 ^\circ C )</th>
<th>III. ( 12.5 ^\circ C \leq T \leq 15 ^\circ C )</th>
<th>VI. ( 15 ^\circ C \leq T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_T )</td>
<td>1</td>
<td>-12.5</td>
<td>-162.5</td>
<td>6.25</td>
</tr>
<tr>
<td>( b_T )</td>
<td>0</td>
<td>4.5</td>
<td>36</td>
<td>-1.125</td>
</tr>
<tr>
<td>( c_T )</td>
<td>0</td>
<td>-0.48</td>
<td>-2.46</td>
<td>0.060</td>
</tr>
<tr>
<td>( d_T )</td>
<td>0</td>
<td>0.016</td>
<td>0.064</td>
<td>-0.001</td>
</tr>
</tbody>
</table>
Electricity demand is satisfied by operation of different types of power plants. Temperature dependency of electricity production varies with the type of power plants. In some base load power plants (hydroelectric and nuclear PPs) electricity is produced independently from temperature. Operation of fossil fuel base load power plants (e.g. lignite PP in Germany) is only slightly affected by temperature. Operation in other power plants can thus depend on temperature changes more than electricity demand does itself. For this reason, power plants are divided into three partitions, one with no temperature dependency in electricity production, one with slight and one with strong temperature dependency. For each PP category, particular temperature dependencies $p_{PP}$ are estimated based on temperature dependent electricity demand and used to calculate temperature dependent emission amounts $EMI_T$ for a particular time period, e.g. one day $d$ in a longer time period with known mean temperature $\overline{T}$:

$$EMI_T(d) = EMI \cdot DF_{pp,y} = EMI \left( 1 + \frac{1}{100} \overline{T(d)} \cdot p_{pp}(T) \cdot dT \right)$$

where

$T(d)$ - mean temperature on day $d$

$DF_{pp}$ - temperature dependent day factor for a PP category.

**The influence of ambient temperature on district heat demand and production**

District heat is used for heating and to a minor degree for domestic and commercial water warming. Heating energy demand is proportional to the difference between indoor and ambient temperature. Assuming that indoor temperature is constant, heating energy demand is proportional to ambient temperature. It is assumed that heating only occurs...
when the daily mean temperature is lower than 12.5 °C and that the highest energy demand for heating occurs at the design temperature of −15 °C. The dependency of heating energy demand $E_{\text{heat}}$ from temperature is shown in Figure 2. It can be described as

\[
E_{\text{heat}}(T) = \frac{100}{35} \cdot (20 - T) \quad \text{in } \% \text{ for } T \leq 12.5 \, ^\circ\text{C}.
\]

\[\text{eq 4}\]

\[
E_{\text{heat}}(T) = 0 \quad \text{in } \% \text{ for } T \leq 12.5 \, ^\circ\text{C}.
\]

\[\text{eq 5}\]

Figure 2: Dependency of heating energy demand from temperature (schematic).

Energy demand for water warming is nearly independent from temperature changes. Thus, it reduces temperature dependency of total district heat demand. It is very difficult to determine the share of temperature independent district heat demand, because consumer structures can be very different in different supply areas. Therefore, a general share of 10 % is assumed. District heat demand $E_{\text{dem}}$ in the heating period then becomes

\[
E_{\text{dem}}(T) = \frac{100}{38.5} \cdot (23.5 - T) \quad \text{in } \% \text{ for } T \leq 12.5 \, ^\circ\text{C}.
\]

\[\text{eq 6}\]

In the temperature range above 12.5 °C district heat demand is approximated with a third order polynomial (cp. eq 2). It is assumed that the demand increases with higher temperatures:

\[
E(12.5 \, ^\circ\text{C}) = 10 \% \quad E'(12.5 \, ^\circ\text{C}) = 0 \%
E(25.0 \, ^\circ\text{C}) = 15 \% \quad E(25.0 \, ^\circ\text{C}) = 0 \%
\]

The relation between $E_{\text{dem}}$ and temperature can then be described as

\[
E_{\text{dem}}(T) = 35 - 4.8 \cdot T + 0.29 \cdot T^2 - 0.01 \cdot T^3 \quad \text{in } \% \text{ for } T > 12.5 \, ^\circ\text{C}.
\]

\[\text{eq 7}\]
In the heating period the derivation of $E_{dem}$ gives a constant increase of demand of 2.86 \%/°C temperature decrease. Temperature influence is lower above the heating limit temperature of 12.5 °C.

District heat demand is satisfied by operation of heat and combined heat and power plants. For HPs, temperature dependency of $E_{dem}$ can be applied directly, while for CHPs temperature dependency of production also depends on the ratio of electricity to heat production. Typically, no information is given with regard to this ratio in emission inventories. Therefore, a general simple method to determine the ratio is applied: temperature dependency of HPs is increased by 40 % to gain temperature dependency for CHPs. The relative influence of temperature is thereby decreased. Heat production in HPs and CHPs $E_{hp}$ and $E_{cp}$ can then be described with

$$E_{hp}(T) = E_{dem}(T) \quad \text{eq 8}$$

$$E_{cp}(T) = \frac{150}{52.5} \cdot (37.5 - T) \quad \text{in [%] for } T \leq 12.5 \degree \text{C} \quad \text{eq 9}$$

$$E_{cp}(T) = 75 - 4.8 \cdot T + 0.29 \cdot T^2 - 0.01 \cdot T^3 \quad \text{in [%] for } T > 12.5 \degree \text{C} \quad \text{eq 10}$$

In Figure 3 the temperature influence on energy conversion in heat and combined heat and power plants is illustrated in comparison with temperature dependency of energy demand for heating, $E_{heat}$. The discontinuity at 12.5 °C occurs because heatings are switched on or off at that temperature.

![Figure 3: Temperature influence on energy conversion in heat plants and in combined heat and power plants in comparison with heating energy demand.](image-url)
Electricity and heat production in fossil fuel power and heat plants shows distinct seasonal variations. In Germany for instance, production is generally lower in summer because of lower energy demand for heating and because of holidays, whereas in Portugal, fossil fuel power and heat plants are mostly needed especially in summer and autumn when there is less hydroelectricity production than in late winter and in spring. Using global monthly factors would thus lead to inaccurate figures. Country specific information is necessary to generate representative monthly factors for Europe.

Monthly factors can be calculated from fuel consumption and energy conversion data from international and national statistics (e.g. EUROSTAT, U N, UCTE) without conducting energy demand analyses. Energy consumption for every month \( (m) \) can then be calculated with eq 11:

\[
EMI(m) = \frac{EMI(y)}{12} \cdot MF(m)
\]

where \( y \) - Index: year.

**Variations due to differentiation of plants for power or heat production**

Though overall amounts of fuel used for heat production are much smaller than fuel amounts used for electricity production, an approach to generate PP-, HP- and CHP specific monthly factors has been developed. It is based on the assumption that ambient temperature has a stronger influence on heat demand than on electricity demand and that heat production has thus a higher seasonality than electricity production.

For HPs and CHPs temperature dependent monthly factors \( MF_{HP,T}(m) \) and \( MF_{CHP,T}(m) \) can be calculated according to

\[
MF_{HP,T}'(m) = \frac{E_{HP}(T(m))}{\sum E_{HP}(T(m))} \cdot 12
\]

\[
MF_{CHP,T}'(m) = \frac{E_{CHP}(T(m))}{\sum E_{CHP}(T(m))} \cdot 12
\]

Heat production in HPs and CHPs, \( E_{HP} \) and \( E_{CHP} \) are calculated according to eq 8, eq 9 and eq 10. To combine temperature dependent monthly factors with the monthly factors calculated from fuel consumption, temperature influence factors TIF and fuel consumption influence factors FIF are defined. For heat plants, temperature influence is assumed to be 100 %. TIF\(_{HP,T}\) therefore becomes 1 and FIF\(_{HP,T}\) becomes 0. In Table 2 the factors are exemplary listed for gas consumption in public power and heat production in Germany.

Table 2: Percentage of gas consumption of gas PPs, HPs and CHPs and temperature and fuel consumption influence factors for Germany, 1990

<table>
<thead>
<tr>
<th>Power plants</th>
<th>Gas consumption share [%]</th>
<th>TIF</th>
<th>FIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat plants</td>
<td>15</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Combined heat and power plants</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
The thus weighed monthly factors are multiplied and standardised to obtain final monthly factors MFPP and MFCHP for HPs and CHPs. Temperature adaptation of HP and CHP monthly factors influences PP monthly factors which can be calculated with the following equation (index F indicates a fuel consumption based monthly factor):

\[ MF_{pp}(m) = \frac{1}{E_{pp}} \cdot (MF_{F}(m) \cdot E_{PP} - MF_{HP}(m) \cdot E_{HP} - MF_{CHP}(m) \cdot E_{CHP}) \]

Total monthly factors based on fuel consumption MFF and specific monthly factors for PPs, HPs and CHPs MFPP, MFHP and MFCHP for Germany, 1990 are shown in Figure 4.

![Figure 4: Total monthly factors MFF based on fuel consumption and specific monthly factors MFPP, MFHP and MFCHP for power plants, heat plants and combined heat and power plants for Germany, 1990.](image)

For the calculation of daily emissions it is primarily necessary to take into account the weekday dependency of energy demand and the dependency from temperature.

**Dependency from weekday**

Habits of energy consumers are strongly influenced by weekday. Thus, power and heat plant operation also shows a distinct weekday variation. Seven weekday factors are applied to determine the relative share of each weekday in overall demand in a specific week. Weekday factors are determined separately for power and heat demand.

**Dependency of district heat demand from weekday**

Weekday dependency of district heat demand is mainly characterised by the types of consumers in a supply area. While commercial demand is lower on weekends, private demand is almost constant during the whole week or slightly higher on weekends. No general information are available about consumer structures. Data that are available for particular district heat supply areas cannot be generalised. Therefore, to determine weekday factors the specifications that are made in VDI (German Association of Engineers) guideline 2067 are applied. The guideline deals with cost accounting of heat supply facilities.
Heat demand is independent from weekday there. Therefore, all weekday factors are assumed to be 1.

Dependency of electricity demand from weekday
In integrated electricity networks differences in consumer structure are compensated. For this reason, information about weekday dependencies of electricity demand that are available from different energy supply companies and other organisations are nearly identical. Mostly, no seasonal variations are accounted for. Weekday factors WF for medium load PPs are taken from a study for VDEW (VDEW 1985) about the determination of grid load curves for electric energy use in German households during one year. From Mondays to Fridays only minor variations occur while demand on weekend days is much lower due to reduced commercial consumption. For peak and base load power plants, specific weekday factors are estimated. For base load PPs, constant operation from Monday till Friday and only a slight decrease of energy production on weekends is assumed, while for peak load PPs, higher production from Monday till Friday and a relatively more pronounced reduction on weekends occurs. The VDEW- medium load weekday factors and the estimated factors for base and peak load PPs are shown in Figure 5. If an attribution of a power plant to either category is impossible because of too little information given in emission inventories, the power plant is treated as a medium load PP.

![Figure 5: Weekday factors for base load, medium load and peak load power plants](image)

Meteorological influences
Knowledge about the influence of different meteorological factors on electricity demand is essential for energy supply companies to guarantee assured and cost-efficient energy supply. Most of the studies in which weather influences on electricity demand are analysed appoint brightness, wind force, air humidity and temperature as main influencing parameters. Information on the dependency between brightness/wind force/air humidity and electricity demand are not conclusive. Here, only temperature influence is taken into account as described in Chapter 2.1.1.1. Temperature dependent daily emissions from power plants can be calculated according to eq 3. For heat plants and for combined heat and power plants daily emissions in a time period \((d=1,...,D_1)\) with known average daily emissions \(EMI\) can be calculated according to...
where \( DF_t \) - temperature dependent day factor.

Calculation of the amount of energy conversion in HPs and in CHPs, \( E_{HP} \) and \( E_{CHP} \), is described in chapter 2.1.1. Daily average temperatures \( T(d) \) for each country are calculated from 7:00 a.m., 2:00 p.m. and 9:00 p.m. national mean temperatures:

\[
EMI(d) = EMI \cdot DF_t(d) = \frac{EMI \cdot \sum_{d=1}^{D_t} E(T(d))}{D_t} \cdot D_E
\]

Calculation of daily emissions

To calculate daily emissions, monthly, weekday and temperature dependent day factors are combined to a day factor and multiplied with annual emissions.

Energy demand is not constant during the day. Variations are taken into account using typical time variation curves for heat and for electricity demand. They only give information about hourly variation. The level of daily emissions is determined by the daily analyses.

Hourly heat demand time-variation curves

In VDI guide line 2067 typical time-variation curves are provided for heat demand. Different curves are given for summer (June, July, August), winter (October till February) and transit time (March, April, May, September). The curves are shown in Figure 6. They are applied only for heat plants. Time curves for combined heat and power plants are based on the considerations for power plants.

Figure 6: Hour factors for heat demand for winter, summer and transit time to represent hourly variations of heat production in heat plants
Hourly electricity demand time-variation curves

Load time-variation in electricity networks is determined by the diurnal rhythm of electricity consumers. It shows a typical low at nighttime and characteristic peaks at daytime. The pattern of grid load during a day can be different in summer and in winter and varies in particular from country to country. The biggest differences occur between northern and southern European countries.

The Union for the Co-ordination of Transmission of Electricity (UCTE) provides grid load diagrams for the third Wednesday of every month. According to inquiries with several energy supply companies time-variation curves are basically the same for weekdays, hence these grid load diagrams are used for all working days. For public holidays, weekday diagrams are modified with an “adaption function” that is generated based on more time-variation curves provided by national experts. The adaption function and standardised time-variation curves for a workday and a holiday in Germany are shown in Figure 7.

Based on annual and monthly statistics, electricity production shares of the following power plant categories are determined:

- Run-of-river power plants and storage power plants
- Nuclear power plants
- Base load power plants (lignite)
- Medium load power plants (coal)
- Peak load power plants (oil/gas)
- Pumped storage power plants

Power plants are assumed to be operated in the hierarchy in which the categories are listed here. Time-variation curves are composed from bottom to top according to the electricity production shares of the power plant categories. Figure 8 shows total hourly loads.
for a Wednesday in May 1990 for Germany (above) and Italy (below) (Source: UCTE) and the distribution to power plant categories.

Figure 8: Total hourly loads for a Wednesday in May 1990 for Germany (above) and Italy (below) (Source: UCTE).
Industry

Greenhouse gases can be discharged into the atmosphere by industrial combustion and by production processes not involving any combustion. Concerning combustion, emissions of CH₄ and N₂O are considered to be negligible compared to CO₂ emissions. Their temporal pattern is identical because all three substances are generated in the combustion process. In industrial production processes, CO₂ contributes the highest share of greenhouse gases emissions as well. Considerable emissions of CH₄ can occur in chemical industry and in some metal production processes. N₂O is a by-product of some production processes, in particular nitric acid and adipic acid production.

2.1.2 Industrial Combustion

Emissions from industrial combustion mainly originate from fossil fuel burning. Hence, it is reasonable to assume that the temporal variation of emissions follows the variation of fuel use. Energy consumption of industrial boilers depends on parameters such as:
- production rates (determining energy consumption for production processes)
- outside temperature (determining energy consumption for space heating)
- production hours, working hours

Data on fuel use with a monthly resolution are available for some countries and can be used to take into account seasonal variations by creating production dependent monthly factors. For countries where such data are not available, monthly fuel use has to be modelled. The same model equation can be applied for the calculation of daily fuel use.

Taking production dependent and temperature dependent fuel use into account as variables, a modelling equation can be set up with regression coefficients describing the relative influence of production and temperature on fuel consumption. The value of the coefficients can be determined for different industrial sectors by reproducing observed fuel use data by a multidimensional regression analysis. Such a regression analysis can be performed for all countries or regions for which appropriate fuel use data is available. The result of the regression analysis is a model equation for the simulation of fuel use data with high temporal resolution. With such a model equation up to daily fuel use can be simulated based on actual production and temperature data.

Different model equations have been set up and tested with regression analyses. The quality of the regression and thus the quality of the model equation was described by the correlation coefficients. The best results have been achieved with a linear model equation including a constant base load ($a_s$), production ($P_{sr}$), temperature ($T_{sr}$), and degree-days ($D_{sr}$) as parameters (Seier, 1998). The resulting model equation for the industrial combustion has the following general structure:

$$E_{sr} = a_s + (b_s * T_{sr}) + (c_s * D_{sr}) + (d_s * P_{sr} * A_{sr})$$

where
- $E_{sr}$: fuel consumption of the sector s in the region r
- $T_{sr}$: mean temperature of the sector s in the region r
- $D_{sr}$: (mean) degree-day of the sector s in the region r
- $P_{sr}$: monthly production index of the sector s in the region r
- $A_{sr}$: daily working time index of the sector s in the region r
- $a_s$, $b_s$, $c_s$, $d_s$: regression coefficients
This model equation allows to calculate monthly, weekly or daily fuel use in industrial sectors. The model parameters have to be provided with the appropriate temporal resolution. Temperature data with high temporal resolution are available from national weather services or from EMEP Meteorological Synthesizing Centres in Oslo and Moscow (http://www.msceast.org). Production indices are available with monthly resolution from international sources like the UN, OECD, and EUROSTAT, or from national statistical offices.

In order to provide a daily estimate of relative production, a working time index has additionally been defined considering reduced working times on weekends. Standardised day factors for Weekdays, Saturdays and Sundays for main economic sectors (Seier 1998) are exemplary shown for Germany in Figure 9.

![Figure 9: Standardised average day factors for main economic categories in Germany](image)

The working time index describes the total working time at all days in the year. Apart from day factors for Weekdays, Saturdays and Sundays, it also takes into account national or local holidays. In GENEMIS a working time index has been defined for all European countries based on calendars and information from national experts. This index considers different holidays in different countries and different national traditions like bridge-holidays and 5 and 6-day working weeks.

It is much more difficult to provide reliable estimates for hourly emissions from industrial combustion sources. If no data on production times during the week and the day exist, it seems to be the most reasonable assumption to relate fuel use and emissions to working times and working shifts. In some countries data on working times and shifts are available from statistics or from industrial surveys. In other countries the calculations have to be based on experts estimates of common working times.

**Uncertainties**

The simulations of monthly and daily fuel use in industry can be considered much more reliable and closer to real patterns than other approaches, because the most important parameters influencing the temporal variation of emissions (production, temperature,
working times) are explicitly taken into account. With this approach, differences from region to region and from year to year due to economic changes or changed climatic conditions are considered. Problems of this approach are caused by the fact that fuel use data of industrial sectors are not available from international statistical offices or institutions. They have to be collected from national and regional authorities and institutes, which requires considerable efforts.

The simulation of fuel use data still produces some uncertainty. The quality of the simulations can hardly be assessed, because fuel use data of industrial sectors or individual industrial plants are only available for a few countries. Simulation results can in most cases not be verified by comparison with real fuel consumption.

2.1.3 Industrial production processes

Industrial production process categories pose severe problems for emission inventoring, as they are characterized by a large number of small, diffuse and heterogeneous emission sources. It is difficult to collect appropriate and reliable data for emission estimates of individual production processes. The same is true for the estimation of the temporal variation of emissions from these sources.

It is a reasonable assumption that emissions from production processes are closely related to production figures of relevant production activities. Useful indicator data, therefore, are production data describing the activity of individual production processes. Such data are usually very hard to find or to estimate.

2.1.3.1 Monthly disaggregation

Due to the lack of detailed production data with high temporal resolution for individual processes in most countries, aggregated monthly production indices have to be applied to estimate a seasonal variation of emissions.

2.1.3.2 Daily and hourly disaggregation

Daily and hourly emissions of production processes can be estimated according to working times.

Uncertainties

The estimations of the temporal variation of emissions from production processes have to be regarded as uncertain due to the lack of detailed statistical data. It has to be assumed that aggregated production data give an estimate for the temporal variation of individual production processes. But this simplification is likely to lead to estimation errors. Nevertheless, within GENEMIS it has been considered more appropriate to consider temporal variations in the way described than to neglect them completely.

2.2 Refineries, extraction and distribution of fossil fuels

Significant amounts of greenhouse gases, basically Methane, come from surface as well as from underground coal mines and from oil and natural gas production, transportation, refining and distribution of fossil fuels.

Refineries and facilities for extraction and distribution of fossil fuels are considered to be generally operated in three shifts 24/7 and with no seasonal variations. Emissions from such plants are therefore assumed to show a uniform annual distribution. This assumption was validated by the participants of the IER CarboEurope GHG workshop in June. LOTOS time factors as well indicate no temporal variation in emission behaviour.

The EMEP Atmospheric emission inventory guidebook proposes a simple and a detailed
methodology for national reporting of emissions from refineries. The latter requires operational data from each plant which could also be used to improve the approach of temporal resolution.

The small consumer combustion category includes households as well as institutional and commercial boilers in public buildings, public and other institutions, workshops, farms, etc. Data about fuel use of small consumers are only available for a few countries and a few sectors, e.g. households. Different types of small consumers, however, usually have different temporal behaviour. The fuel consumption of households is mainly used for space heating (about 80-90%) and to a smaller extent for hot water production (about 10-20%). As investigations in Germany and Hungary have shown (Fahl, 1989), commercial small consumers’ fuel consumption is partly dedicated to heating purposes and partly to production processes. It is assumed that the production dependent fuel use is directly related to working times. The strong dependency on degree-days leads to strong seasonal variations of small consumer emissions, while the dependency on working-times contributes to a strong hourly variation.

The following modelling equation is suggested for the simulation of monthly or daily small consumer fuel use:

\[ E_{r} = s_{0} + (s_{1} D_{r} + s_{2} H_{r} + s_{3} A_{r} + s_{4} n_{r} n_{d} + s_{5} A_{r} n_{a}) \]

where:
- \( E_{r} \) is the small consumers relative fuel consumption in the region \( r \)
- \( D_{r} \) is the degree-day of the region \( r \)
- \( H_{r} \) is the heating-season index for the region \( r \)
- \( A_{r} \) is the working-time index for the region \( r \)
- \( n_{r} \) and \( n_{d} \) are the normalization factors for degree-days and working-time indices
- \( s_{0} \) is the contribution of constant base load of small consumer fuel use
- \( s_{1}, s_{2} \) are the share-factors describing the contribution of fuel use for heating and production

The heating-season index only has to be used for regions or countries where district heat is available for a limited season (e.g., 15 October - 15 April in Hungary). Days without limitation of heating (non-heating days) are characterized by the value \( H = 1 \). The share factors \( s_{1} \) and \( s_{2} \) are estimated based on national expert opinions. According to estimations from national experts within GENEMIS it is suggested to distinguish Western and Eastern European countries and define share-factors and heating-season-indices as given in Table 3. If no more detailed information is available, those share-factors are used for households, commercial and institutional plants.
In Central and Eastern European countries fuel consumption is assumed to be on a rather high level throughout the year, as a large amount of fuel is used for hot water and cooking. This is especially true for households with single coal or wood stoves that contribute a considerable share to total small consumer emissions. The share-factors given in the table represent default-factors, which can be used as long as no better information is available.

For the hourly distribution of small consumer emissions hourly patterns of fuel use for heating purposes and hourly patterns of production related fuel use have to be estimated. Within GENEMIS production related fuel use had been assumed to correspond to typical daily working times. The hourly variation of heating related fuel use, however, depends very much on the heating technology, climatic conditions and on insulation standards.

For central-heating a correlation with ambient temperature can be assumed, alongside a reduction at night-time. For single coal or wood stoves a very strong morning and late-afternoon or evening peak can be observed. This pattern is due to fuelling the stoves in the early morning and after returning home from work. Hourly patterns for households have been derived from an evaluation of a comprehensive survey in Germany in VDI norm 2067. They are shown in Chapter 2.1.1.4, Figure 6. If no other information exist about commercial and institutional plants, their hourly patterns can be assumed to coincide with the variations in household combustion activities. More detailed information can be derived from surveys in different groups of small consumers, conducted e.g. by (Seier, 1998). The results of this survey are exemplary shown as typical daily time-variation curves for hotels and restaurants, wholesale and retail sale, hospitals, schools, non-profit institutions and swimming pools in Baden-Württemberg, Germany in Figure 10.
Uncertainties

The small consumer combustion model provides reasonable results for the temporal variation of emissions. Uncertainties, however, are assumed to be significant. In the case of small consumers the assumption of a linear relation between total fuel use and emissions may lead to errors, as a large variety of very different small consumers with different heating technologies, different fuels, and different behaviours exist. As the availability of fuel consumption data with high temporal resolution is very limited, it is not possible to verify the modelling approach and the choice of constants in the model equation in greater detail.

Road traffic belongs to the most important emission sources in Europe. It displays very strong temporal variations of emissions. While different vehicle types show a similar temporal behaviour, different road types like motorways, rural roads and urban roads show different patterns of road traffic densities and thus emissions. Monthly variations of road traffic emissions can be gathered from monthly national energy statistics available from EUROSTAT (EUROSTAT, 2003), but the level of detail would be relatively low because factors like e.g. type of road could not be taken into account. More information like the influence of time and day in the season, day in the week, weather conditions, working times, etc. can be derived from traffic flow data. Traffic flow data are usually available in the form of traffic counts (automatic or manual), which represent an excellent empirical base for the estimation of the temporal variation of emissions, because all external factors are implicitly considered. However, traffic count data on a global scale are not available from international statistical offices, but only from national authorities. In some countries it is extremely difficult to obtain appropriate traffic counts or traffic density data.

Traffic count data can be available in different states of evaluation and data processing. In some countries original data from counting stations are available. Due to a high number of counting stations and a big amount of data for every single station, such data require a further evaluation that causes considerable efforts. In other countries (e.g. in Germany) counting data are associated to characteristic monthly, daily, and hourly traffic density curves annually calculated with cluster analyses (e.g. (Straßenwesen, 1991)). In case of Austria and Germany an average traffic density can be calculated. In other cases a monthly traffic density index is available for different road types (e.g. in France, INSEE 1990). This index gives an average road traffic density for all motorways and rural roads and can be assumed to be a good indicator for the monthly variation of traffic emissions.

Road traffic emissions show strong seasonal as well as strong hourly variations. They display a stronger seasonal variation for motorways than for rural and urban roads, and a stronger seasonal variation in rural areas than in urban areas. Hourly variations, instead, are quite similar for different road types and regions. In Figure 11 weekly average traffic densities are shown for motorways, rural roads, and urban roads for the German federal state of Schleswig-Holstein in 1986. Schleswig-Holstein represents a rather rural area with a lower population density than the average in Germany. It is strongly affected by holiday traffic to the North Sea and the Baltic Sea, and from and to the Scandinavian countries.
The influence of holiday traffic can clearly be seen especially on weekly motorway traffic density, which shows characteristic peaks at spring and summer holidays and strong minima at winter holidays. During the summer holiday season, traffic density and thus road traffic emissions on motorways were more than 50% higher than traffic density and emissions in the winter. Similar results hold for other years and other regions. Weekly rural and urban traffic density is more continuous. In spring and summer holidays, urban traffic is partly shifted from urban roads to motorways and from urban regions to rural areas, as can clearly be observed for Eastern 1986.

Road traffic is also characterized by very strong hourly variations. Emission peaks at daytime are 6-7 times as high as the lowest emissions at night-time. This feature can clearly be observed in Figure 12, where hourly road traffic densities are presented for Monday to Sunday in the federal state of Schleswig-Holstein. Average hourly road traffic counts for the Greek city of Thessalonica show even stronger emissions in the evening than load patterns for Germany. This condition is typical for Mediterranean countries.
Uncertainties

The availability of road traffic counts poses one of the main problems. Within GENEMIS traffic counts have as yet only been available for Germany, Austria, France, and Greece. Moreover, it is hard to assess the representativeness and reliability of the data available. A major problem is often caused by the large amount of road traffic data with unsatisfactory homogeneity and quality caused by varying data structures, data gaps, or errors, which hampers automatic processing. The examination and evaluation of such data, therefore, can be extremely time consuming.

Regions and countries without any traffic count data available have to be treated with the temporal patterns based on data from other regions. For sure, this generalization causes significant errors and reduces the accuracy of the data calculated. However, more sophisticated simulations for such regions are not possible, as road traffic density is a very complex function of many parameters. Patterns such as the degree of urbanisation, regional and local driving preferences etc. can thus not be easily assessed.

2.5 Other mobile Sources

The category “Other mobile sources” comprises air, ship and railway traffic, and off-road vehicles. The estimation of the temporal variation of emissions requires data on traffic activity with high temporal resolution.

For the estimation of aircraft-emissions with high temporal resolution at airports, landing-take-off cycles (LTO cycles), passenger numbers and freight statistics, which are available from airports or from the International Air Traffic Association (IATA), provide the best information available. The hourly emissions from Air traffic can usually be assumed to be distributed over the day without strong variations, while no emissions occur during nighttime (usually between 23 pm and 6 am) due to night-flight interdiction on many airports.

For the estimation of ship traffic emissions with high temporal resolution the number of passing ships per hour, day, week, or months in harbours or on ship routes is directly related to the temporal distribution of ship emissions and provides a reasonable indicator, though different ship types show different emission behaviour. However, it is usually hard to find appropriate data. In the case of complete lack of data it seems reasonable to assume an equal distribution over the year and over the day.

Within GENEMIS, off-road vehicle traffic has not been covered due to a lack of data. According to other studies a more detailed treatment may be needed for off-road-vehicles, which seem to be responsible for a considerable contribution to total emissions and also are likely to show important temporal variations of emissions (Zierock, 1994). As a first estimate, it could be assumed that off-road vehicle emissions are higher in the summer and at day-time and lower in the winter and at night-time (e.g. construction machinery in the construction sector, agricultural tractors etc.)

Shortcomings of these approaches are likely to be caused mainly by a lack of reliable data.

2.6 Waste

Treatment and disposal of solid and liquid waste can release CO$_2$, CH$_4$ and N$_2$O and other greenhouse gases. In the IPCC Guidelines Reference Manual, CO$_2$ emissions from the decomposition of organic material derived from biomass sources (e.g. crops, forests) which are regrown on an annual basis are not treated as net emissions from waste. CH$_4$ is considered to be the most important gas that is emitted from waste treatment and disposal plants. It is a product of anaerobic decomposition of waste or waste water com-
2.6.1 Monthly, daily and hourly disaggregation

Components and accounts for 5 - 20 per cent of annual global anthropogenic CH₄ emissions (IPCC 1996). CH₄ production in waste treatment and disposal plants depends on:

- Waste amount and composition (degradable organic matter)
- Waste disposal practices
- Temperature

Waste amount and composition give information about CO₂ and CH₄ generation potential. Seasonal influences such as e.g. higher usage of private composting facilities in summer or disposal of Christmas trees in January can change amounts and composition to a small extent, but no detailed information defining monthly or seasonal amount and composition changes are available.

The influence of amount and composition changes is regarded minor compared to waste disposal practices. The latter are considered to be the biggest influence on emissions of greenhouse gases in this source category but it is assumed that they rather influence total emissions than the temporal variation of emissions in a year. Temperature in landfills is of great importance for the methane generation potential and thus also for emissions, but seasonal ambient temperature changes have no significant influence on waste temperature in layers deeper than two metres below surface. The energy released by biodegradation keeps the temperature in the landfill at 25 - 40 °C. Temperature changes in aerobic surface layers may change the methane degradation potential and lead to lower emissions in the summer (Börjesson, 1996), but research results indicate contradictory patterns. In composting plants, methane generation should be negligible because during composting, only aerobic conditions should occur.

Emissions from landfills, incineration plants and sewage treatment plants are assumed to be constant during the year and to show no significant daily or hourly variations. This assumption is based on the facts mentioned above and was approved by the participants in the IER CarboEurope GHG workshop that was held in June and in personal communications (Institute for Sanitary Engineering, Water Quality and Solid Waste Management, University of Stuttgart, 09.2003).
3. Spatial Resolution

National greenhouse gas emissions are reported to the Intergovernmental Panel on Climate Change (IPCC) by all parties to the United Nations Framework Convention on Climate Change (UNFCCC). Higher spatial resolution than national total data as it is currently reported is required because regional variations of anthropogenic emissions can be significant. National emission data can be further resolved by intersection with e.g. land use data and digital road and railway maps. Where available, emission data on NUTS 2 or NUTS 3 level instead of national emission data should be used for intersection with land use data to further improve the spatial resolution. Emission data on NUTS 2 or NUTS 3 level can be generated using statistical information with the respective level of resolution as allocation parameters. Such allocation parameters can be the number of inhabitants, number of employees in different branches, number of farms and animals, etc. Appropriate parameters must be determined for every emission activity and correlated to emission amounts to be usable as allocation parameters.

According to their geographic structure, point, line and area emission sources can be distinguished. Emissions from each source type require different information for spatial resolution:

3.1 Large Point Sources

In (EMEP/CORINAIR, 1996) the following emission sources are considered large point sources. Their geographical location is clearly defined by their coordinates.

- Power plants with a thermal capacity $\geq 300$ MW
- Refineries
- Nitric acid and sulphuric acid production plants
- Iron & steel plants with a production capacity of $\geq 3$ Mt/a
- Paper & pulp industry with a production capacity of $\geq 100$ kt/a
- Automotive paint shops with a capacity of $\geq 100000$ cars per annum
- Airports with at least 100000 landing-takeoff-cycles per annum
- All other sources emitting more than 1000 t SO$_2$, NO, or more than 300 kt CO$_2$ per annum.

The last category includes district heating plants, waste incineration plants and various industrial production and combustion plants. The geographical coordinates of point sources were taken from the CORINAIR inventories or were determined by surveys with the help of country experts. More up to date data are currently only collected in the frame of the EC Large Combustion Plants Directive (LCPD) and in the upcoming European Pollutant Emission Register (EPER) (http://www.eper.de/).

3.2 Line Sources

Routes of transportation of passengers and cargo are line sources: roads, railways, ships and pipelines. For these line sources, GIS based vector data are available, mostly for transnational railways, inland waterways, highways and federal roads.
3.2.1 Road traffic and railway traffic

Due to the high density of roads in urban areas, urban traffic is treated as an area source. Rural and highway traffic is attributed to line sources with the aid of a digital European road network (ESRI, 1993). The average length of a street section between two points of the digital road network is 1.5 km. Emissions from railway traffic as well are localised with the ESRI digital European network.

3.2.2 Shipping

Shipping includes activities at sea, in port and on inland waterways. The coastline separates national from international shipping (Schwarz, 2002). Emissions from national shipping are mostly much lower than emissions from international shipping. They only account for 0 - 2 % of total CH₄ and N₂O emissions in European countries (EMEP/CORINAIR, 1996), but their share in CO₂ emissions may add up to 40 % in some countries.

Emissions from inland waterway transportation can be located with the aid of land use data. Emissions of SO₂, NOₓ, NMVOC, and CO have been calculated by EMEP (Jonson, 2000) with a spatial resolution of 50 x 50 km from which the spatial distribution of emissions of greenhouse gases can be derived as emissions are proportional to fuel consumption.

3.2.3 Air traffic

Emissions from air traffic occur during LTO’s (landing-and-takeoff-cycles, limited by a height of 1000 m and including activities on ground like taxi and idle) and during cruise (any air traffic activity above 1000 m). LTO’s are allocated to airports and attributed to the category of large point sources.

Spatial disaggregation of cruising activities might in the simplest case be based on repetitive flight schedules assuming that flight routes are always in linear distance between takeoff and landing site. According to (Kalivoda 1997), much more detailed data about air traffic movements is available from the European Organisation for safety of air navigation (EUROCONTROL) which will have to be examined in order to verify their usability.

3.3 Area sources

All emission sources that neither belong to point nor to line sources are classified as area sources. Area sources comprise all activities which are diffuse, attributed to a large number of small individual sources or have indistinct spatial patterns, e.g., urban traffic, household emissions and small industrial and commercial plant emissions. National emission data (and where available, data on NUTS 2 or 3 level) are spatially resolved by intersection with the CORINE land use data that are available for western Europe from (EEA, 1997) with a resolution of 250 m × 250 m. This dataset was generated in the scope of the CORINE - Programme (CoO Rdination, Information, Environment). An update for a year 2000 dataset is in progress and expected to be finished in 2004 (Buttner, 2003).

References


  land cover data update completed for: Netherlands, Ireland, Latvia, Malta. For other European countries: in progress, project expected to finish in 2004.


Regarding carbon balance in connection to the agricultural sector, three greenhouse gases are of importance and have to be considered: carbon dioxide, methane and nitrous oxide. According to the results of the IER CarboEurope GHG workshop no sophisticated models are available yet for determining the temporal patterns of CO₂, CH₄ and N₂O emissions. More information is available about the temporal variability of agricultural ammonia emissions, but since emissions of CO₂, CH₄ and N₂O are not necessarily equally distributed, they have to be investigated separately. This chapter gives an overview over helpful literature and possible approaches for modelling of temporal variations of emissions from agriculture.

In the context of this work package of the CarboEurope GHG project only anthropogenic emissions are addressed. Therefore, only emissions are considered which are emitted during animal housing and manure storage. Emissions which occur before the application of manure or fertilizer on agricultural land are addressed in another work package.

### 4.1 Carbon dioxide

In animal husbandry, Carbon dioxide is emitted from animal metabolism and from decomposition of litter and manure. In the context of additional anthropogenic CO₂ emissions, these sources need not to be considered since they do not affect atmospheric CO₂ concentration in the medium and long terms. Therefore, CO₂ emissions from animal husbandry are not regarded in common GHG inventories. These fluxes of recent CO₂ are, however, necessary for a carbon balance across all sectors of human activity in a given region although they do not contribute to global warming. Examples for measured CO₂ emissions from animal husbandry give, e.g. Langeveld et al. (1997), Nesor et al. (1997), Kaiser and van den Weghe (1997) or Dosch and Gutser (1996).

The main factors of influence for CO₂ emissions from animal metabolism are (Gallmann, 2003):
- (metabolic) Live weight and production status,
- Respiratory quotient,
- Heat increment,
- Feed uptake, composition and quality of feed,
- Gross- and net energy, metabolisable energy, digestibility of feed,
- Retention of nutrients,
- Temperature,
- Animal activity.

Models are available for respiration of pigs, e.g. van’t Klooster & Heitlager (1994), van Ouwerkerk & Pedersen (1994), Ni (1998), Niebaum (2001). These models differ mainly in influencing factors considered as for example animal weight, feed properties and others. Models for cattle respiration are based on measurements in respiration chambers and regard as well animal and feed characteristics.
4.1.1.1 Spatial resolution

Spatial resolution is expected to be possible on NUTS2 level.

4.1.1.2 Temporal resolution

**Seasonal disaggregation:**
One influencing factor on temporal (annual) variability in agriculture is the particular production status. As production over the year is kept as constant as possible, no seasonality is expected for indoor husbandry (mainly cattle, pigs and poultry) in contrast to outdoor husbandry (mainly sheep and goats). Production rates of cattle, pigs and poultry are mainly kept constant during the year while outdoors, seasonal population variations can be caused by natural reproduction cycles. Pig-related emissions may as well depend on agronomic „pig cycle“, the cyclical variation of pig market prices. For estimating this fluctuation data about the pig meat offer can be used.

**Hourly disaggregation:**
Variation of emissions during one day follows animal activity, even so in the case of CO₂. CO₂ emissions from e.g. pigs show a typical variations of about 20% of mean daily respiration. The activity is mainly influenced by times of feeding, drinking and resting and thus shows a clear day/night-rhythm. The typical course of emissions is examined by e.g. Comberg & Wolfermann (1964), Hahne et al. (1999), Hinz & Linke (1998), Kaiser (1999), Mayer (1999).

**Data requirements and data sources:**
It is expected that the following data is needed:
- Animal numbers
- Animals kept outdoors or in-house
- Animal performance (e.g. milk yield, growth,...)
- Feed ration: amounts and composition (also if produced on-farm or are bought-in).

Animal numbers are available on European NUTS2-level, provided e.g. by EUROSTAT (http://europa.eu.int/comm/eurostat/Public/datashop/print-catalogue/DE?catalogue=Eurostat)

However, numerous other information needed such as farm structure, distribution of farms, farm types and farm management is not available on European level with a sufficient degree of accuracy. There exist different approaches to meet this problems; One of them is the work of ELPEN – European Livestock Policy Evaluation Network (http://www.mluri.sari.ac.uk/elpen/index.htm).

The objective of the ELPEN project is to build a state-of-the-art integrative, knowledge-based, spatially explicit decision support system to appraise the likely impact of policy change on the livestock sector. The system will integrate bio-geographical data (on soils, climate, topography, land cover, etc.) with statistical data and other information on technical, economic, environmental and social aspects of livestock systems. It will incorporate expert knowledge and display integrated, indicative results of the economic, environmental and social impacts of policy change.

Other sources of information about details on farm structure and farm management could be results of the ongoing work of FAL (Federal Agricultural Research Centre,
Braunschweig/Germany) and of KTBL (Association for Technology and Structures in Agriculture), especially the study from DÖHLER et al. (2001).

**Expected difficulty:**
As aforementioned only little information is available on farm management. It will probably be necessary to resort to national expert knowledge.

### 4.1.2 Manure emissions

As pointed out before, CO\(_2\) is formed during the decomposition of manure and litter. Despite different research efforts the CO\(_2\) emission situation from excreta and straw in the animal house and storage is quite uncertain. It is influenced by the type of animal house, aeration, storage type for manure and slurry and temperature during storage. Measurements show that manure accounts for 0 to 50% of CO\(_2\) emissions from e.g. pig houses. There is a positive correlation between NH\(_3\) and CO\(_2\) losses from manure, so the temporal patterns may be comparable, but only very preliminary quantitative data are available.

Data are available on NUTS2 level.

#### 4.1.2.1 Spatial resolution

**Seasonal disaggregation:**
Temporal variability is dependent mainly on temperature and on grazing period, but it is unclear how big and relevant the amplitude of the seasonality is. Concerning pig-related emissions, the „pig cycle“ might also have an influence (see above).

**Hourly disaggregation:**
No detailed information are available about hourly emission variations, but it seems reasonable to assume a day/night-rhythm caused by the influence of temperature.

**Data requirements and data sources:**
In the main the same data is needed as for CO\(_2\) from animal metabolism (cf. 1.2) That is e.g. animal numbers, housing systems, animal performance, feed rations etc.

### 4.2 Methane

Methane has two important sources considering animal husbandry: on one hand enteric fermentation of ruminants and secondly emissions from animal houses and manure management.

Enteric fermentation is a digestion process in which carbohydrates are broken down by micro-organisms into simple molecules. Microbial fermentation permits utilisation of cellulose of grasses, but it is a process connected with a loss of energy by the release of CH\(_4\), CO\(_2\) and heat.

The amount of released CH\(_4\) depends on the following factors:
- (metabolic) live weight, daily weight gain, production status;
- feed uptake, -composition, -digestibility;
Methane emissions from animal houses are influenced by housing characteristics such as manure systems, aeration and air temperature, type of floor and activity of animals.

Methane emissions from enteric fermentation has been widely addressed in the last 40 years, so there is a huge amount of measured data in Europe. There are several standard approaches for assessing CH₄ emissions from enteric fermentation which differ in their degree of disaggregation of animal types. The EEA (1996) methodology to evaluate, on an annual basis, the national CH₄ emission from enteric fermentation of herbivorous is based upon the following three steps:
1. Evaluation of the daily emission per type of animal, including the major sources of variation,
2. Integration of these daily emissions on an annual basis, taking into account time variation in animal activities, and finally
3. Integration of the national livestock.

To evaluate annual emissions it is necessary to integrate from one day to one year through a modelling approach, taking into account the variation factors for each kind of animal, especially the nutritional supply and its variations during the year.

For assessing enteric fermentation from ruminants there exist algorithms which are supposed to be satisfactory. They determine CH₄ emissions per animal in dependency of feed ration, feed properties etc., one of them is the so called “Kirchgessner-equation” (Kirchgessner et al., 1991). This approach may need a lot of detail information about feeding strategies, which can be roughly obtained from farm survey statistics. The importance of this detail information for CH₄ emissions remains unclear. In regional average, the approach by IPCC (1997) may be simpler and precise enough. To reach a decision a sensitivity test with the “Kirchgessner-equation” versus IPCC equation would be needed.

Data are available on NUTS2 level.

### 4.2.1 Animal emission

#### 4.2.1.1 Spatial resolution

#### 4.2.1.2 Temporal resolution

**Seasonal disaggregation:**
As production throughout the year is kept as constant as possible, no seasonality is expected.

**Hourly disaggregation:**
Diurnal variability follows animal activity as it is the case for CO₂. Some first modelling attempts of diurnal variability of CH₄ emissions are in progress.
For stored and land-spread manures, temperature influences the rate of emission and probably also ultimate CH₄ generation. Oxygen availability and hence moisture content of farmyard manures is also a strong influence, since methane generation is inherently an anaerobic process.

In addition, CH₄ emissions from manure depend on:

- type of manure management and storage system,
- type of manure or residues (influence the maximum methane production capacity),
- the C/N-ratio and the pH inside the manure,
- the pre-treatment and handling of the manure.

The quantification of this CH₄ emission source is still afflicted with uncertainties, particularly due to different CH₄ generation potentials of different types of manure that have to be considered. From this it follows that the definition of a particular methane conversion factor for each manure system is necessary. This factor says which part of the total generation potential is under certain conditions effectively transformed to CH₄.

Data are available on NUTS2 level.

Seasonal disaggregation:
The seasonal variability of CH₄ emissions from manure is discussed controversial. Nevertheless, some studies show increasing emission during summer time due to higher ambient temperature (Rathmer, 2002; Niebaum, 2001).

Hourly disaggregation:
Little knowledge exists about daily variability, but a positive correlation with animal activity is probable and indicates a typical day/night-rhythm.

For Data requirements and availability see also 1.3.

There is no direct N₂O generation from animal metabolism, only emissions from manure and slurry storage have to be considered. (These emissions from manure and slurry application are however dealt within another part of the project; close collaboration for harmonisation of data is anticipated).

N₂O emissions from slurry are expected to be very low and no seasonality was detected. IPCC emission factors or regional emission factors as suggested by Freibauer et al. (2001) would be adequate. In the case of farmyard manure, only little data is available, though emissions are more significant. As for slurry, IPCC emission factors or regional emission factors are recommended.

Overall, N₂O emissions from manure storage are small as compared to other sources and not accurately described. No temporal patterns can be considered.
4.4 Uncertainties and comments

1) Measurement error 20-30%, hopefully not systematic
2) Error due to averaging of results for emission factor: derive probability distribution, normally log-normal
3) IPCC provides default values for uncertainty in statistics.

Uncertainty analysis should cover 1) uncertainty in magnitude of emissions, 2) uncertainty in trends of emissions, 3) correlation between influencing factors.

Comment:
Units of emission factors contain some ambiguity. A „year“ is not unambiguously defined in terms of animal-days or year-days, etc. Best use units for N-gases (N₂O, NH₃) as % of N excreted, for C-gases (CH₄, CO₂) per animal and day (give weight of animal), or related to feed energy or standard animal unit.

References
• MAYER, C. (1999): Stalhklimatische, ethologische und klinische Untersuchungen zur Tiergerechtigkeit unterschiedlicher Haltungssysteme in
der Schweinemast. Schriftenreihe der Eidgenössischen Forschungsanstalt für Agrarwirtschaft und Landtechnik FAT Nr. 50, Dissertation technische Universität München, ISSN 0257-9200.


• Executive Summary

Scope
Currently, greenhouse gas emission data are calculated and reported on an annual and national basis in Europe. On the other hand, for modelling purposes, hourly emission data on a 10 km * 10 km grid are needed, for instance to be used for the development and operation of a satellite emission monitoring system. Hence, methods for the temporal and spatial resolution of the most important greenhouse gas emissions (CO₂, CH₄, N₂O) are presented and discussed in this report.

At first, temporal variations of emissions from emission source groups with similar temporal activity patterns (e.g. public power, small consumer combustion, road traffic) are discussed. In a second step, the spatial resolution based on the classification of emission source types (area, line and point sources) is described. The temporal and spatial resolution of emissions from agriculture - as a rather new topic in the calculation of high resolution emission data - is treated separately because the methods applied are still in an early state of development.

Approach
To obtain emission data with a high temporal resolution, standardised monthly, daily and hourly time factors are generated and multiplied with annual emissions. To generate such time factors, statistical data must be compiled and processed which gives information about temporal variations of emission source activity rates. Data availability varies greatly with the individual source groups. Quite robust data is available for public power generation. Sufficient information on industrial activity rates is available only for some regions. Hence, information must be transferred and applied also in regions where no statistics are available. The situation is simpler for refineries, extraction and distribution of fossil fuels and waste treatment and disposal. Typically, their activity rates and emissions are constant throughout the year due to continuous operation. Concerning small consumer combustion (in households, commercial and institutional plants), emissions mainly depend on ambient temperature. Data availability is no problem in this case, however, the functional dependency should be further investigated to improve the accuracy of emission calculation. Where road transport is concerned, automatic traffic counts are a very good basis for the temporal resolution of road traffic emissions, but their compilation and processing causes enormous efforts and is not yet conducted by a central statistical institution. Other mobile sources comprise air, ship and railway traffic and off-road vehicles. This source group and its data situation is very inhomogeneous. Useful information can be taken from flight and railway schedules, but most difficulties occur for off-road vehicles.

To generate emission data with high spatial resolution, national emission data or emission data on NUTS² 2 or NUTS 3 level are intersected with land use data, attributed to line sources with the aid of a digital European road and railway network or, in case of point sources, accounted for by using their coordinates. Updated land use data for
the year 2000 are expected to be completed and available in 2004.

Methods to calculate temporal variations of agricultural emissions have been developed for ammonia, but yet, no readily usable method for the temporal and spatial resolution of agricultural greenhouse gas emissions is available. The concepts that were discussed during the CarboEurope GHG workshop in Stuttgart in June, 2003, are presented.

Conclusions
The key issue in temporal and spatial resolution of GHG emission data is the availability of statistical data about emission source activity rates. The GENEMIS disaggregation methods can be regarded as a foundation for the development of an emission monitoring system, but their efficient application requires more detailed input data from central statistical institutions. Partly, data compiled in the scope of GENEMIS have to be used until more up-to-date, comprehensive and consistent European datasets are available. Collaboration with institutions such as EUROSTAT, UCTE (Union for the Co-ordination of Transmission of Electricity) and EUROCONTROL (European Organisation for the safety of Air Navigation) need to be intensified and other data sources must be opened up to improve the quality of the calculated emissions.

1 e.g. to IPCC, the EC and the UNECE
2 NUTS = EU Nomenclature of Territorial Units for Statistics