Planning for Increased Bioenergy use –
Strategies for Minimising Environmental Impacts and Analysing the Consequences

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Abstract

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There are several goals aimed at increasing the use of renewable energy in the Swedish energy system. Bioenergy is one important renewable energy source and there is a potential to increase its use in the future.

This thesis aimed to develop and analyse strategies and tools that could be used when planning for conversion to bioenergy-based heating systems and the building of new residential areas with bioenergy-based heating. The goal was to enable the increase of bioenergy and simultaneously minimise the negative health effects caused by emissions associated with the combustion of bioenergy.

The thesis consists of two papers. Paper I concerned existing residential areas and conversion from electric heating and individual heating systems, such as firewood and oil boilers, to more modern and low-emitting pellet techniques and small-scale district heating. Paper II concerned new residential areas and how to integrate bioenergy-based heating systems that cause impacts on local air quality into the physical planning process through using Geographical Information Systems (GIS) and a meteorological dispersion model, ALARM.

The results from Paper I indicated that it was possible to convert areas currently using electric heating to pellet techniques and small-scale district heating without degrading local air quality. Furthermore, it was possible to decrease high emissions caused by firewood boilers by replacing them with pellet boilers. The results from Paper II highlighted that GIS and ALARM were advantageous for analysing local air quality characteristics when planning for new residential areas and before a residential area is built: thus, avoiding negative impacts caused by bioenergy-based combustion.

In conclusion, the work procedures developed in this thesis can be used to counteract negative impacts on local air quality with increasing use of bioenergy in the heating system. Analysis of potentially negative aspects before conversion to bioenergy-based heating systems, or before bioenergy-based heating systems are installed in new residential areas, make it possible to avoid these heating systems in areas with sensitive air quality characteristics, and to increase bioenergy use without causing negative impacts on local air quality and potential health risks to the inhabitants in such areas.

Keywords: Bioenergy; Small Scale; Combustion; PM10; Benzene; GIS; Dispersion modelling; Environmental impacts; Physical planning; Local Air quality

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Till Ida!

Contents

Appendix

Papers I – II

This thesis is based on the following papers, which are referred to in the text by their corresponding Roman numerals. Paper I is appended and reproduced with kind permission of the publishers.

I. Jonsson, A & Hillring, B. 2006. Planning for increased bioenergy use – Evaluating the impact on local air quality. *Biomass and Bioenergy 30, 543 - 554*

II. Jonsson, A & Hillring, B. 2006. GIS and dispersion calculations as tools for integrating air quality aspects into physical planning. *Manuscript*

Note on the authorship of the papers

For Paper I and II, the planning was performed by Anna Jonsson and Bengt Hillring. The data was collected, modelled, analysed and interpreted by Jonsson. Jonsson wrote the papers with comments from Hillring. He was also responsible for the final revision.

Introduction

What is bioenergy?

Bioenergy, or biofuels, has been defined by different standardisation organisations in the world. The European Union defines biofuels as “a fuel produced directly or indirectly from biomass (European Committee for Standardization, 2003)”. The same standard defines biomass as “a material of biological origin excluding material embedded in geological formations and transformed to fossil”.

Bioenergy is used in both large-scale appliances, such as district heating or combined heat and power plants, as well as small-scale heating systems for heating houses (boilers and stoves) and as a complementary heat source and feel good factor (stoves and open stoves).

Different forms of bioenergy

Bioenergy is a comprehensive name for fuels made from biomass (Ljungblom, 1994). Bioenergy can be divided into non-refined and refined biofuels. The raw material is most often forest residues (such as wood logs, tops and branches, bark and sawdust) and energy crops. Non-refined fuels are the raw material cut into smaller pieces; whereas, refined fuels are ground into wood powder or compressed to wood briquettes or wood pellets. Refined biofuels have lower moisture content, are more homogenous and have higher energy density than non-refined biofuels (NUTEK, 1996).

Non-refined biofuels

Firewood

Firewood is cut and oven-ready fuel wood used in household wood burning appliances such as stoves, fireplaces and central heating systems (European Committee for Standardization, 2003). The quality of firewood is crucial to how beneficial it is from an environmental viewpoint and factors affecting this are for example moisture content and the technique used (Johansson *et al.*, 2003). Optimal moisture content for firewood is below 20 per cent and the length is typically in the range 150 mm to 1000 mm (European Committee for Standardization, 2003).

Wood chips

Wood chips originating from woody biomass are cut into pieces by mechanical treatment, such as knives. The shape of wood chips is sub rectangular and the length is 5 to 50 mm, the thickness is lower than the other dimensions (European Committee for Standardization, 2003). Wood chips are mainly used in larger appliances, such as district heating plants. During the 1970s, wood chips were common for small-scale heating, but because of the high moisture content (30-50 per cent) in combination with a large surface area, mould and fungus often infected the wood chips and became a health risk for people living in the houses (Tarstad, 1994).

Refined biofuels

Wood pellets

Wood pellets (here referred to as “pellets”) are used both for small-scale heat production and in district heating plants. Pellets are cylindrical in form and with a random length, typically 5 to 40 mm and have broken ends (European Committee for Standardization, 2003). For Swedish conditions, pellets are usually 6 – 12 mm in diameter and 10 – 20 mm in length (NUTEK, 1996). During production, the raw product (usually sawdust and other by-products from the forest industry) is ground into a fine powder and compressed under high pressure and temperature (Hadders, 2002). The high pressure softens the lignin and it becomes a bonding agent: thus, no additives are needed.

Wood briquettes

Wood briquettes (here referred to as briquettes) are produced in the same way as pellets. They are cubic or cylindrical in form (European Committee for Standardization, 2003), the diameter is 50 – 76 mm and the length is 2 – 20 cm (NUTEK, 1996). Briquettes are mainly used in large-scale appliances such as district heating plants.

Liquid and gaseous biofuels

Liquid and gaseous biofuels, such as ethanol, rapeseed methyl ester (RME) and biogas, are becoming more commonly used in for example cars and buses as a replacement for fossil fuels (SVEBIO, 2004).

Bioenergy in Sweden – then and now

Bioenergy, particularly firewood, has a long history in Sweden. Firewood was the main fuel for heating, lighting and cooking until the mid 20th century. In 1730, concerns about the supply of firewood and deforestation of the Swedish forest arose (Larsson, 1979). An at that time normal household of ten people consumed 50 cubic meters of firewood per year and firewood was expensive, especially for the urban population. The price of firewood more than doubled compared to other goods between 1780 and 1860. As a result, ceramic tiled stoves became common, as they were more efficient than open stoves. In 1920, coal and coke were introduced and stoves using these fuels became popular, as well as central heating. Except for a small increase in the use of firewood during the Second World War, the use of oil dominated the heating market after its introduction in 1930. (Kaijser, 2001) With the oil crisis in 1970 and extensive development of nuclear power in Sweden, electric heating became the most common heating system for residential and commercial premises (Kaijser, 2001) and electric heating still comprises a large portion of the heating market (Andreasson *et al.*, 2005).

Today, the price of electricity and oil are rising (Statistics Sweden, 2006; The Swedish Petroleum Institute, 2006). There are several environmental goals aimed at decreasing the greenhouse gas emissions and the use of fossil fuels and decreasing the amount of electricity used for heating (Anon., 2001b; Anon., 2002; Anon., 2006). Since 1970, the use of bioenergy in the energy system in Sweden has increased by over 100 per cent, from 155 PJ in 1970 to 387.5 PJ in 2004 (Statistics Sweden, 2005). The amount of bioenergy used for small-scale heating of dwellings and non-residential premises was 39 PJ in 2004, which was 25 per cent of the total small-scale energy use in these kinds of buildings (Andreasson*, et al.*, 2005), this figure includes the use of both firewood and pellets.

A common distribution system for heat inside a house in Sweden is water-based radiator systems with circulating water. There are also air-borne systems, where the heat is distributed in canals between different rooms in the house, but this system is rather uncommon. In houses with electric base board, no distribution system for the heat is present; instead, each radiator works as a heat source itself.

Bioenergy – advantages and disadvantages

Bioenergy is a renewable, carbon dioxide neutral energy source and has therefore many benefits for the Swedish energy system. It is a domestic energy source and there are enough raw materials to increase usage (Parikka, 2004), which will help decrease green house gas emissions.

However, bioenergy also has disadvantages. Small-scale use of bioenergy may cause severe impacts on local air quality. If bioenergy, particularly firewood, is used in combustion units that are old and have inefficient technique, incorrect procedures are used when managing the fire, or if fuels have a high moisture content, emissions of for example particles, polyaromatic hydrocarbons (PAH) and volatile organic compounds (VOC), may be released into the surrounding air (Johansson*, et al.*, 2003). A summary of CO_2 and particle emissions from common small-scale heating systems in Sweden is found in Table 1. Particles increase the risk of cardiovascular and respiratory diseases (Dominici *et al.*, 2006) and vulnerable groups are asthmatics, elderly people and children (Ahlbom *et al.*, 2005; Clancy *et al.*, 2002; Kunzli *et al.*, 2000). PAH is potentially carcinogenic and influences many stages in the cancer infection process. PAH also affects the respiratory organs and is especially irritating for asthmatics. VOC is a large group of different substances and the impacts vary from creating ground level ozone and being carcinogenic to increasing the green house effect. (The Swedish Energy Agency, 2003) Air quality in Sweden is regulated by the Environmental Code (Anon., 1998). Environmental standards are present for a number of pollutants, the standard for particles, PM_{10} is shown in Table 2.

Table 1. Emissions from bioenergy and other common small-scale heating systems

Heating system	CO_2 (mg/MJ)	Particles (g/MJ)
Old type firewood boiler	0	87 – 2200 *
Modern wood boiler	0	18 – 89 *
Pellet boiler	0	13 – 64 *
Oil boiler	75000**	6 – 12 *
Electric heating[1]	7842***	2.5***

[1] Corresponds to total environmental impact for electricity applied to the Swedish national grid 1999.

* (Johansson *et al.*, 2004)
**(Uppenberg *et al.*, 2001b)
***(Uppenberg *et al.*, 2001a)

Table 2. Environmental air quality standards for particles, PM_{10} (Anon., 2001a)

Mean value period	Environmental quality standard	Comment
24 hours	50 $\mu g/m^3$	May be exceeded up to 35 times / yr (90-percentile)
1 year	40 $\mu g/m^3$	Arithmetic average

Objective

This project arose because of the positive aspects of bioenergy, a renewable energy source that to a substantial part can replace oil and electricity in space-heating systems. The use of bioenergy makes it easier to achieve global environmental goals and move a step closer to a sustainable society. However, bioenergy can cause negative impacts, such as local emissions of particles and other health hazardous pollutants. If the positive aspects of bioenergy are to be gained and an increase of the energy source to be possible, it is important to simultaneously minimise negative impacts.

Aim

The aim was to develop and analyse strategies and tools that could be used when planning for conversion to bioenergy-based heating systems and the building of new residential areas with bioenergy-based heating. The goal was to enable an increase in bioenergy and simultaneously minimise the negative health effects caused by emissions associated with the combustion of bioenergy.

Delimitation

The project was limited to emissions from small-scale space heating for residential premises[1]. The geographical areas studied comprised existing residential areas and areas that were in the planning process. The fuels analysed were firewood, pellets, oil and electricity. Emissions were limited to particles and benzene (a form of VOC).

[1] Small-scale heating systems are in this thesis defined as heating systems with an installed power < 0.5 MW_{th}. Small-scale district heating is defined as a concept similar to district heating, but with an installed power < 10 MW_{th} which is rather small for Swedish conditions.

Materials and methods

The methods used in this thesis can be divided into theoretical methods used for designing the studies and practical methods used for the modelling of scenarios and visualising results. In both papers, case study methodology was used as the theoretical method and Geographical Information Systems (GIS) and a meteorological dispersion model, Advanced Local and Regional Modelling system, ALARM (Enger KM-Konsult AB, 2005) was used as the practical methods.

Background of methods

Case study methodology

The case study methodology in this thesis followed the structure of design and performance described by Yin (1989a). According to Yin (1989a), case studies are a suitable tool when questions including "how" and "why" are to be answered. Furthermore, a case study *"investigates a contemporary phenomenon within its real-life context; when the boundaries between the phenomenon and context are not clearly evident; and in which multiple sources of evidence are used"* (Yin, 1989b). Therefore, case studies can be used advantageously for researching issues on sustainability (Corcoran, Walker & Wals, 2004). The design of a case study according to Yin (1989a) follows a number of steps:

- Question to be answered
    - How and why questions
- Propositions
    - What is being studied?
- Units of analysis
    - What units are being collected, what kind of data etc?
- The logic linking of data to the propositions
    - How the units analysed help to prove the answers?
- The criteria for interpreting the findings
    - What do different findings mean? Statistics, etc.

There are three different types of case studies described in Yin (1989a): exploratory, explanatory and descriptive. Exploratory case studies involve fieldwork and data collection to answer the research questions and hypothesis stated. Explanatory case studies include casual studies and may include pattern-matching techniques. Descriptive case studies begin with a descriptive theory and form hypotheses on cause-effect relationships.

Geographical Information Systems

GIS has been developed from various scientific disciplines (Arnberg *et al.*, 2003). The definition used in this thesis is the same as the one used by ESRI, which is the developer of the software used in Papers I and II (ESRI, 2006):

"GIS is a collection of computer hardware, software, and geographic data for capturing, managing, analysing, and displaying all forms of geographically referenced information"

GIS can be used for the management, analysis and display of geographical knowledge. The system is used in different disciplines, for example business (advertisement, logistics, telephone companies etc), local authorities (physical planning, health and security, emergency services etc) and research (modelling, visualising results etc) (Arnberg*, et al.*, 2003).

A GIS is built up by maps, globes, geographic data sets and data models (ESRI, 2001). Maps and globes provide interactive views of geographical data, which make it possible to answer questions, present results and use the software as an instrument when working with projects. Geographical data sets are data- and file bases containing geographical information features, networks, topologies, terrains, surveys and attributes. Data models allow the inclusion of advanced behaviour and integrity rules.

When working with GIS, aspects of the world are presented in the form of geographical objects. There are:

- sets of points, lines and polygons, which are vector based
- raster datasets, such as digital elevation models and images
- networks
- terrains
- survey measurements
- other types of information, for example addresses, place names, cartographic information

All these different geographical objects are organised into thematic layers (see Figure 1) and tables. The objects are georeferenced and because of this, spatial relationships such as areas, distances, changes in elevation etc. can be obtained through GIS. Tables with information on each object are connected to each layer. In these tables, more information can be added or transformed (for example through calculations). Different tables can be obtained and connected to each other based on their spatial characteristics.

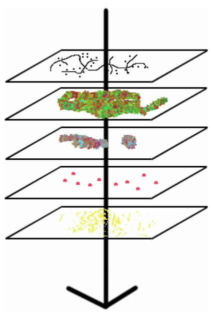

Figure 1. Thematic layers in GIS

ALARM

The dispersion model used in this project was ALARM (Enger KM-Konsult AB, 2005). ALARM performs dispersion calculations for point-, line- and surface sources, as well as for emissions from buildings. Dispersion calculations are also possible for single occasions, such as accidents and for both mean and percentile values: local terrain, wind and turbulence fields are included in the calculations. The model can also be used for calculating wind energy. The output data from the model consists of concentrations from source or sources at a certain time, prognosis for up to 12 hours, mean value or percentile concentrations. Emissions from different sources, potential wind energy and meteorological data and statistics are also obtainable. (Haeger-Eugensson *et al.*, 2002) The input data for calculating point sources needed are:

- Coordinates for each chimney
- Specific emission factor for each chimney (grams/second)
- Chimney height (m)
- Flue gas temperature (°C)
- Emission flow (m^3/s)
- Inner chimney diameter (m)
- Outer chimney diameter (m)
- Building height (for surrounding buildings)
- Building width (for surrounding buildings)

The model is validated in several studies in Sweden, Greece and USA (Älvsborgs Air Pollution Prevention Association, 2001).

How the methods were used

Case study methodology

The case studies in Papers I and II were explanatory, with dispersion calculations as a survey tool. The subject of study was in both papers a geographical area, and the theoretical question to be answered was concerning different aspects of air quality. In Paper I, five case study areas were chosen, and it was therefore a multiple case study. In Paper II, only one case study area was analysed and it was a single case study. Both papers covered smaller geographical areas. In Paper I, the case study areas were residential blocks. In Paper II, a slightly larger area with eight residential blocks was analysed. The designs of the case studies are summarised in Table 3.

Table 3. Designs of the case studies in Papers I and II

Step in the design process	Paper I	Paper II
Question to be answered	"How does future conversion to small-scale bioenergy-based heating systems affect the local air quality?"	"How can GIS and ALARM integrate the fact that bioenergy-based small-scale heating systems could cause negative impacts on local air quality in the planning process of new residential areas?"
What was being studied?	Contribution of pollutants after conversion to bioenergy-based heating systems in five different geographical areas	Ways of analysing sensitive areas for bioenergy-related air pollutants in future residential area
Units of analysis	Mean value concentrations and percentile concentrations of PM_{10} and benzene from small-scale pellet and firewood heating and small-scale district heating systems	Concentrations and dispersion patterns from a pollutant with emission factor 1 g/s was modelled in ALARM Changes in elevation was obtained through mapping in GIS
The logic linking of data to the propositions	Mean value concentrations and percentile concentrations of PM_{10} and benzene from small-scale pellet and firewood heating and small-scale district heating systems	The dispersion pattern of the pollutant and its concentrations promoted analysis of which parts of the future residential area would obtain the largest concentrations of pollutants The elevation analysis indicated the parts of the area that were lowly situated and which had rapid changes in elevation. Such areas may be sensitive to irritating and health hazardous pollutants
The criteria for interpreting the findings	The results from the dispersion calculations were compared to Environmental Quality Standards to determine if they breached the standards in the areas studied	The sensitive areas were identified through visual interpretation The lower areas were identified by finding the parts with lower than average elevation within the case study area

Geographical information systems

As the studies in this thesis concerned geographical areas, GIS was the main tool in both papers. It was used to obtain and visualise results through thematic layers and thematic tables with various information. A summary of the ways GIS was used in the papers is presented in Table 4.

Table 4. Usage of GIS in Papers I and II.

Purpose	Paper I	Paper II
Calculating data	X	X
Calculating areas	X	
Calculating elevation		X
Calculating emission information	X	X
Obtaining coordinate information	X	X
Visualising results	X	X

ALARM

ALARM (Enger KM-Konsult AB, 2005) was used in Papers I and II. The main objective with using ALARM in Paper I was to obtain concentrations and dispersion patterns for the pollutants PM_{10} and benzene within the case study areas. The amount of PM_{10} and benzene emitted from each chimney was calculated by the emission factors and energy use and then added to ALARM. For the input data used in Paper I, see Table 5.

Table 5. Input data for ALARM used in Paper I (Svenson, 2003).

Parameter	Individual boilers	Small scale district heating
Coordinates for each chimney		
Specific emission factor for each	See Paper I	See Paper I
Chimney height (m)	4.5	20
Flue gas temperature (°C)	20	35
Emission flow (m^3/s)	1	0.6
Inner chimney diameter (m)	0.18	0.2
Outer chimney diameter (m)	0.8	0.4
Surrounding buildings:		
Height (m)	4.4	4.4
Width (m)	9.0	9.0

In Paper II, the main objective with ALARM was to receive dispersion patterns of pollutants emitted from planned chimneys in a future residential area. No statistics about emissions or energy use were needed, as the dispersion pattern, not the actual emissions were analysed. For the input data used in Paper II, see Table 6. The emission factor was therefore set to 1 g/s. If the concentrations of a certain pollutant were required, the relation between 1 g/s and the emission factor of the pollutant was the same as the relation between the concentrations. Emission factors for bioenergy-based fuels are often given in the form of mg/MJ: with formulas 1 and 2, mg/MJ converts to g/s:

Annual energy need (MJ/year) X emission factor (mg/MJ) = mg/year *(1)*

$$mg/year = 0.001\ g/3153600\ s = 3.17 * 10^{-9}\ g/s$$
$$\rightarrow 1\ mg/year = 3.17 * 10^{-9}\ g/s \qquad (2)$$

Table 6. Input data for ALARM used in Paper II (Björkman, 2005).

Parameter	Individual boilers
Coordinates for each chimney	
Specific emission factor for each chimney (g/s)	1
Chimney height (m)	6
Flue gas temperature (°C)	300
Emission flow (m^3/s)	0.02
Inner chimney diameter (m)	0.16
Outer chimney diameter (m)	1.5
Surrounding buildings:	
Height (m)	5.5
Width (m)	12

There are several other dispersion models available in Sweden, for example Air Viro (Wickström, 2006) and Dispersion (SMHI, 2006). Paper I was written in cooperation with The Air Pollution Prevention Association in the South West of Sweden, who use ALARM for modelling purposes. Therefore, ALARM was used in Paper I and was the natural option for Paper II to make it easier to compare the results.

Results

Paper I

In Paper I, five case study areas, numbered 1-5, were analysed with the aim "How does future conversion to small-scale bioenergy-based heating systems affect local air quality?". In the first three areas, 1-3, the contributions of PM_{10} and benzene on conversion from electric heating to pellet technique and small-scale district heating were studied. It was assumed that no emission sources were present in the area and dispersion calculations were therefore only for future heating sources. For pellet technique, the same concentrations were found close to the chimneys: for the dispersion patterns in Areas 1-3, see Figures 6-8 in Paper I.

In Areas 4 and 5, firewood was the main fuel used. Therefore, dispersion calculations for PM_{10} and benzene were performed for both existing heating systems and for conversion to pellet technique. In Area 5, conversion to small-scale district heating was analysed (this was not an option in Area 4) and a number of scenarios with different emission factors were performed.

In Area 4, the heating systems currently used caused an accumulation of pollutants in the southern and central parts of the area. On conversion to pellets, the emissions accumulated in the northern parts of the area, see Figure 9 in Paper I: for maximum concentrations in Areas 1-4, see Table 6 below.

Table 7. Contribution of PM_{10} and benzene from combustion of bioenergy in Areas 1-4, the highest concentrations observed in the dispersion calculations, given in μg/m^3. Fields marked with (-) has not been investigated in the area concerned.

Area	Existing boilers		Conversion to pellet		Conversion to small scale district heating	
	PM_{10}	Benzene	PM_{10}	Benzene	PM_{10}	Benzene
Area 1, mean values	(-)	(-)	0.5	0.03	0.002	0.0005
Area 1, 98-percentile	(-)	(-)	1.0	0.08	0.025	0.005
Area 2, mean values	(-)	(-)	0.325	0.025	0.05	0.001
Area 2, 98-percentile	(-)	(-)	1.5	0.10	0.05	0.01
Area 3, mean values	(-)	(-)	0.25	0.02	0.025	0.0005
Area 3, 98-percentile	(-)	(-)	0.75	0.05	0.5	0.015
Area 4, mean values	10.0	0.5	0.10	0.035	(-)	(-)
Area 4, 98-percentile	30.0	1.5	0.25	0.0075	(-)	(-)

In Area 5, the parts that tended to accumulate air pollutants were in the north and centre of the area. This accumulation occurred in all scenarios and independently of technique. The pollutants from the small-scale district heating system affected the southeast parts of the area. For dispersion pattern in Area 5, see Figure 10 in Paper I, and for maximum concentrations, see Table 7 below.

Table 8. Contribution of PM_{10} and benzene from combustion of bioenergy in Area 5: the highest concentrations observed in the dispersion calculations, given in µg/m^3. Fields marked with (-) has not been investigated in the concerned dispersion calculation.

Dispersion calculation	A		B		C		D		E		F	
Concentrations	PM_{10}	Benzene	PM_{10}	Benzene	PM_{10}	Benzene	PM_{10}	Benzene	PM_{10}	Benzene	PM_{10}	Benzene
Mean values	0.025-0.1	0.01-0.03	(-)	(-)	0.05-0.25	0.005-0.015	0.25-1.0	0.02-0.1	0.005-0.03	0.0005-0.003	0.0001-0.03	0.0001-0.00075
98-percentile	0.25-0.5	0.05-0.125	0.75-1.25	0.2-0.4	0.5-1.25	0.05-0.075	3.0-4.0	0.25-0.4	0.05-0.15	0.005-0.015	0.05-0.5	0.001-0.1

Paper II

In Paper II, the case study answered the question "How can GIS and ALARM integrate the fact that bioenergy-based small-scale heating systems could cause negative impacts on local air quality in the planning process of new residential areas?". An overview map of the case study area is seen in Figure 1 in Paper II. Elevation and wind analysis, as well as dispersion calculations, were performed in ALARM. Low elevated parts of an area may accumulate pollutants due to less air dispersion. Furthermore, rapid changes in elevation may result in a chimney on one house being on the same elevation as a window or terrace or fresh-air inlet in another house.

The elevation analysis indicated that the north and eastern parts of the case study area were the lowest elevated parts (below average elevation in the area). Rapid changes in elevation were seen in the housing areas A, E, and F; see Figure 2 in Paper II. The wind analysis determined that the dominant wind directions were south, southeast and southwest; see Figure 3 in Paper II. As a result, wind reaching the northern, lower situated parts may have slowed down and be polluted by emissions from the southern parts.

From dispersion calculations, the highest mean concentrations (over 1000 $\mu g/m^3$, corresponding to where pollutants tend to accumulate, not the actual concentrations) were found in future residential areas D and E; otherwise, emissions appeared to spread evenly throughout the area, see Figure 4 in Paper II. The highest 98-percentile concentrations (over 9000 $\mu g/m^3$) were found in the eastern part of the area and the second highest 98-percentile concentrations (over 7000 $\mu g/m^3$) were seen in the central, northern and eastern part of the area; see Figure 5 in Paper II.

Discussion and conclusions

Bioenergy and air quality in existing residential areas

One conclusion from the results in Paper I, is that the current heating system in the areas analysed can be converted to pellet technique or to small-scale district heating without exceeding environmental quality standards. Therefore, there is potential through conversion to increase the amount of bioenergy-based fuels used in the heating system, provided no other large emission sources are situated close to the areas. When choosing between small-scale district heating and pellet technique in Areas 1-3 in Paper I, small-scale district heating was preferable from an air quality point of view. Installing small-scale district heating in a house that currently uses electric heating is a large and expensive operation, as electric heating does not use water-based heat-distribution systems, which small-scale district heating does. However, for the pollutants investigated, pellet technique did not markedly affect air quality and is a possible option for conversion. In Areas 4 and 5, where emissions from current heating systems were also investigated, a decrease in the emissions was determined when the current heating systems were converted to pellet technique or small-scale district heating. The concentrations of pollutants in all areas were probably higher than the results predict during some periods of the year and lower in other periods, as variations in energy consumption changes due to outside temperature and meteorological aspects, such as inversion.

Dispersion modelling as a method for investigating the contribution of air pollutants from bioenergy-based combustion is advantageous, as shown in Paper I. To avoid insecurities with a model (the output data is never better than the input data), measurements can verify the results; however, measurements are only possible if the chimneys already exist. When planning for conversion of heating systems, modelling future concentrations is one useful way of investigating and predicting air concentrations. Even though the actual concentrations might be insecure, the dispersion pattern should be reliable and locations within an area that are sensitive to air pollutants can be identified.

Bioenergy and air quality in future residential areas

One way of integrating GIS and ALARM in the physical planning process was highlighted in Paper II. A picture of which parts of the future residential area are sensitive to air pollutants can be obtained through dispersion calculations and visualising the results in GIS. Paper II began with an analysis of the topographical characteristics and the dominant wind directions in the case study area. This provided an idea about which parts of the area may accumulate air pollutants, but the most precise means of receiving information about air pollutants in Paper II was by dispersion calculations. Combining an overview map in GIS with the results from a dispersion model, such as ALARM, provides a good picture of what the air pollution situation will resemble when the area is built. To this map, further information can be added, for example measurements of background concentrations.

The disadvantages of bioenergy should be considered in the different levels of planning, from comprehensive planning to detailed development planning and from municipal energy planning to house owners, who plan their own heat supply and who are the actual users and the ones becoming exposed to the pollutants. The work procedure used in Paper II could be a tool for integrating this information.

Why residential areas with single family houses?

The papers in this thesis dealt with two different aspects of pollutants associated with bioenergy in residential areas. Paper I analysed how conversion from electric heating and firewood boilers to modern pellet technique and small-scale district heating with bioenergy-based fuels affected the local air quality. Paper II presented an analysis of how to integrate local air quality into the physical planning processes, with GIS and ALARM as tools, without taking any emission factors from specific heating systems or fuels into account. In the case studies in both papers, the houses built are single-family houses and detached or semi-detached. These kinds of houses are important when increasing the amount of bioenergy used in the heating system, as they often use individual heating systems and bioenergy is a suitable option.

Furthermore, in such residential areas, electric heating is one of the largest heating systems currently used. As political goals aim to decrease the use of electricity for heating, complimentary heat sources and information on how modern bioenergy-based heating affect the local air quality are important. In areas with electric heating, and areas with firewood boilers and oil boilers that will eventually be replaced with modern techniques, it is possible to install pellet techniques, but it is important to analyse the consequences before a new residential area is built, as was done in Paper I. Building new residential areas with bioenergy-based heating systems could be expensive if it turns out that the areas has bad air quality characteristics. Integrating GIS maps with layers including dispersion calculations allows incorporation of air quality into the physical planning process.

Increasing the use of bioenergy without impacts on air quality

When planning for an increase of bioenergy-based heating systems in the kinds of areas analysed in this thesis, the work procedures developed in Papers I and II can be used. However, they are somewhat different to each other. In Paper I, the energy needed for heating each house was calculated to be able to obtain the actual concentrations in the five different case study areas. This was not performed in Paper II because the task was to investigate dispersion patterns and sensitive parts of the case study area. Despite these differences, the different work procedures do not exclude each other. It is possible to perform a dispersion calculation for only the dispersion pattern, and analyse sensitive spots in an existing area about to be converted to bioenergy-based heating. Furthermore, it is possible to calculate the actual emissions and future concentrations in an area not yet built. Generally, it is easier and more convenient to calculate the dispersion pattern and not the energy need for heating and emission factors, although results that are more realistic will be obtained if the actual amount of pollutants emitted is calculated.

Increasing bioenergy use in the different kinds of areas has different purposes and challenges. Old firewood boilers in existing residential areas may cause large emissions of bioenergy-related pollutants. In those areas, the task is more to avoid negative health effects than increase the bioenergy used in the system, as firewood is classed as a renewable energy source. Converting electric heating to pellet technique or to small-scale district heating is important from a global environmental view, as 66 per cent of global electricity production originates from coal, oil or gas, and only 8.3 per cent from biomass (IEA, 2003). To ensure sustainable heating systems in the future, renewable energy, such as bioenergy-based heating systems, could be installed in areas with no risk of high concentrations of pollutants or smoke emanating from neighbouring chimneys and becoming an irritant to the inhabitants.

Conclusion

The aim in this thesis was to develop and analyse strategies and tools that could be used when planning for conversion to bioenergy-based heating systems and the building of new residential areas with bioenergy-based heating. The goal was to enable an increase in bioenergy and simultaneously minimise the negative health effects caused by emissions associated with the combustion of bioenergy.

The work procedures presented in this thesis were developed during the work with Papers I and II. In conclusion, these work procedures can be used as tools to counteract negative impacts on local air quality with increasing use of bioenergy in the heating system. They can also be used as strategies for visualising future concentrations of air pollutants and for integrating the risks of bioenergy at different levels of planning. The work procedures make it possible to carefully increase the bioenergy used in the Swedish heating system without degrading local air quality.

Future research

A limitation to using the work procedures developed in this thesis is that they are based on modelling and not measurement. The output of models is never better than the input and with small-scale bioenergy-based combustion, emission factors are hard to obtain and predict, at least emission factors for firewood. Emissions from firewood boilers and stoves depend on how the fire is managed: each house owner develops his/her own way of managing their equipment, and if this behaviour in some way includes moist fuel, old technique, or lack of oxygen in the fire, high emissions may occur. When trying to decrease the bioenergy-related emissions in an area, future research should therefore include an analysis of the role of combustion procedures and analysis of emission factors from different kinds of equipment and behaviour. Further applications of GIS could be health maps indicating where it is unsuitable to build premises housing vulnerable groups, for example hospitals, schools or homes for elderly people.

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