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URBAN DISTRICT ENERGY FUTURES: A DYNAMIC MATERIAL FLOW ANALYSIS (MFA) MODEL

N. Filchakova[1], H.-P. Bader[2], R. Scheidegger[2], D. Robinson[1] and J.-L. Scartezzini[1]

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ABSTRACT

With more than half the world population now urbanised, urban metabolism – defined as the throughput and transformation of material and energy flows to sustain human life in urban settlements – is responsible for consuming the majority of global resources and the impact that this has on the environment. The identification, quantification and analysis of the main stocks and flows of energy and matter can support decision-making for a more sustainable urban resource use.

Material Flow Analysis (MFA) is a method that has been widely used to study the metabolism of anthropogenic systems at a variety of scales. Yet the scale of the urban district has been addressed only scarcely. Often an established municipal unit for the purpose of planning, decision making and implementation, it is this district scale which is the subject of our study.

In this we first present a mathematical MFA model (MMFA) for the simulation of energy and matter flows within our chosen urban district (Matthäus, Basle). We then go on to describe how this model was calibrated to this district. Various scenarios (with a special focus on energy) for the future optimisation of this status quo are discussed. We conclude by suggesting some promising strategies for the more sustainable development of Matthäus during the next fifteen years.

INTRODUCTION

In this paper, we analyse the energy use in an urban district by applying the MFA method [1]. Our objective here is to highlight the potentials that can be exploited during the next 10-15 years to reduce the district's resource consumption while meeting the living needs of its population. In this, we study possible pathways by which the district's energy balance may evolve up to the year 2020. We also assess what values of key indicators, such as total domestic consumption and associated green house gas emissions, could be attained under various scenarios.

In particular our study aims to demonstrate what changes (on the demand and/or the supply side) should be implemented to achieve a certain set of urban sustainability objectives.

Our chosen case study site is the district of Matthäus in Basle - an old centrally-located part of the city (Fig.1). This district is known for having the highest population density in Basle (391,4 p./ha). It is industry-free but accommodates several hundred small-scale local service and trade businesses.

METHOD

Mathematical Material Flow Analysis (MMFA) is a method for the description and (dynamic) simulation of material flows in a given system. Developed by Baccini and Bader, the method has been applied in a variety of fields and at a variety of scales – though most often at the regional scale. The methodology of MMFA is explained in detail in [1]. In brief this consists of four steps: (1) 'system analysis' where system borders, the processes involved and their material and energy flows are identified; (2) 'mathematical description' where a system of time dependent equations for the considered flows is formulated, taking into account specific properties of the system (parameter functions); (3) 'calibration'; and (4) 'simulation' and interpretation of results.

System analysis

The energy module of our MFA model consists of two sub-modules: heating and electricity. These energy resources are supplied to residential and non-residential users (comprising local district trades, services and enterprises; but excluding industry and transport).

The district heat demand in Matthäus is covered by various sources of energy, both non-renewable and renewable. In our model these input flows are treated separately in order to vary the split in our future scenarios regarding energy supply (Fig.1, right).

Electricity is provided centrally from the city's 'industrial services'. This is a mix of power produced outside of Basle, internal generation from a large waste incineration plant and from PV installations. We do not consider changes in this domain nor do we include planned pilot projects to exploit geothermal heat or to incinerate wood; because these lie beyond the boundaries of our study district.

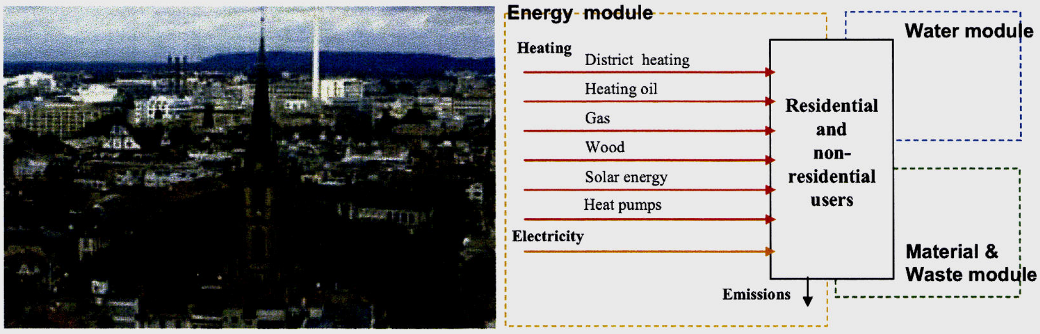

Figure 1: Left: The district of Matthäus, Basle (Source: www.statistik-bs.ch). Right: System analysis of district metabolism.

Mathematical description

The balance of heat and electricity demand and supply for the district serves as a basis for the mathematical description of the system. For each energy carrier, respectively, the input flow can be calculated as follows:

$$I_i(t) = P(t)P_u(t)f_i(t) \quad (1),$$

where $I_i(t)$ is the *i*-th input flow (*TJ/a*), $P(t)$ is the district population, $P_u(t)$ is the use-specific (non)residential demand for heat/electricity ($MJ/C \cdot a$) and $f_i(t)$ is the fractional use of *i*-th energy source (district heating, oil, gas, wood and solar energy), $i = 1-5$ for residential and 6-10 for non-residential users respectively.

Emissions resulting from the use of oil or gas for heating are easily obtained from the expression $E_i(t) = c_i I_i(t)$, where c_i is the specific CO_2 emission factor *(t/TJ)*.

Calibration

The model was calibrated using available data for the period 2000-2005 [2, 3]. For electricity, data from 1995 was obtained to better capture the consumption pattern. Based on this and assumptions about the future (scenarios), four parameter functions describing specific demand $P_u(t) = \{P_{rh}(t), P_{re}(t), P_{nrh}(t), P_{nre}(t)\}$, where the subscripts stand for (*n*on)*r*esidential *h*eat/*e*lectricity demand, and ten fractions of specific energy suppliers $f_i(t)$ were defined. The assumptions underlying our scenarios (which inevitably entail some subjectivity [4]) are described below.

Scenarios

With a mathematical description of our system (Eq.1), different possible futures can be examined based on assumed or forecasted changes to (non)residential energy supply or demand. To this end, three scenarios for the period 2005-2020 have been modelled and compared (Table 1):

1. Business as usual (BAU). All parameters are kept at the 2005 level.
2. Moderate. Heat and electricity demand reduction, accompanied by a gradual repartition of supply fractions and an increase of solar energy utilisation.
3. Extreme. Strong reduction in heat demand, electricity demand and supply fractions as in Scenario 2.

Parameter function	Scenario	Development 2005-2020	Reference value source
District population *P(t)*	all	const	15650 [3]
Res. heat demand $P_{rh}(t)$	BAU	const	17550 $MJ/C \cdot a$ [4]
	moderate	Twofold linear decrease *	
	extreme	Fourfold linear decrease *	
Fractions of heat sources in households $f_i(t), i=1-5$	BAU	const	0,358/ 0,333 /0,265/ 0,014/ 0,01 [5]
	mod./extreme	See Fig.2 **	
Spec. emissions c_i	all	const	84 *t/TJ* (oil), 57 *t/TJ* (gas)
Non-res. heat demand $P_{nrh}(t)$	BAU	const	23000 $MJ/w \cdot a$ *w=worker* [3]
	moderate	1,5-fold linear decrease	
Fractions of heat sources for non-res. uses $f_i(t), i=6-10$	all	as for residential uses	[5, see in text]
Res. electricity demand $P_{re}(t)$	BAU	const	5820 $MJ/C \cdot a$ [2004, 2]
	mod./extreme	Gaussian to 1995 level***	4880 $MJ/C \cdot a$ [1995, 2]
Non-res. electricity demand $P_{nre}(t)$	BAU	const	17500 $MJ/w \cdot a$ [2004, 2]
	mod./extreme	Gaussian to 1995 level***	14000 $MJ/w \cdot a$ [1995, 2]
Streetlight electricity demand	all	const	0,73 MJ/m^2

Table 1: Parameter functions P(t) and modelled scenarios.

* Heat demand: There is considerable potential to decrease heat demand in Matthäus. In such an old district, refurbishment alone can yield a four-fold reduction in energy use (cf. [6]). Further measures to reduce heat consumption include fuel prices, taxes and education. The suggested scenarios correspond also to the goals of the 2000W society, which requires a three-fold reduction of (total per capita) energy consumption (comprising all (non)residential building uses as well as transport) from today's level.

** Fractions: For solar heat utilisation, a step-wise growth from 1% to at least 2% of residential buildings served by these installations is anticipated (which is an approximation of a logistic implementation function proposed in [4]). Oil is expected to be superseded by gas (continuing the tendency from 1990 [5]) and district heating. The district heating network might possibly be expanded following historical growth trends (as has happened in Lausanne for example). Taking into account that 50% of Basle households are today supplied by district heating, we assume that at least the same target could be set by 'industrial services' for Matthäus.

*** Electricity demand: Electricity consumption has been growing over the last decade. This trend is assumed to continue until 2010 and to then descend to at least the 1995 level thereafter. A function that can describe such development is Gaussian-like; asymmetric with respect to its maximum. This corresponds also to the function that is conventionally used to describe the diffusion of innovation [7]: in this case, development and adaptation of new electrical appliances.

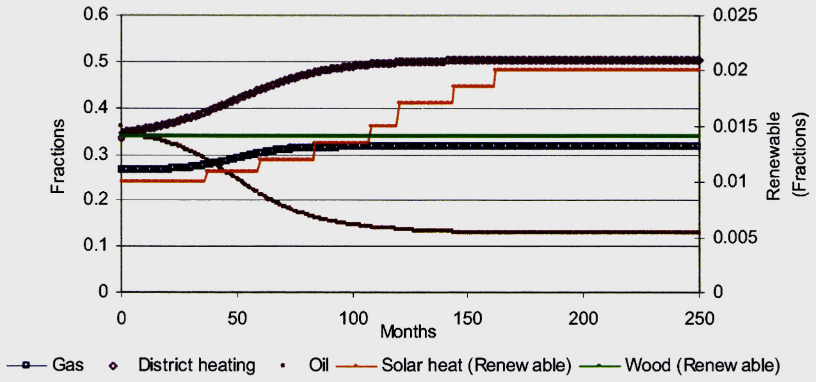

Fig. 2. Fractions of different heat energy carriers serving the district's households (2000-2020).

RESULTS

The evolution of the district's household heat consumption according to our three scenarios, for each considered energy source is shown in Fig. 3.

In both (alternative) scenarios, where we assume a deliberate fuel switch together with demand-side reduction, a strong reduction of energy consumption by 2020 is observed. Moreover, we observe that a decline of oil consumption for heating purposes to almost zero could be attained by 2020. Heating needs nevertheless remain large enough that locally converted solar energy may be progressively exploited (cf. "input solar energy" in the moderate scenario, Fig.3).

Furthermore, the simulation results in Fig.3 show that if the heat source fractions evolve from 2000 as projected in Fig. 2, the district and gas-based inputs will reach their maxima by about 2008, to compensate for a sharply decreasing oil supply. Then, due to optimisation of energy use on the demand side, the district heating input will approximate the BAU level in scenario two, whereas under the more extreme scenario it will descend to half of the status quo level.

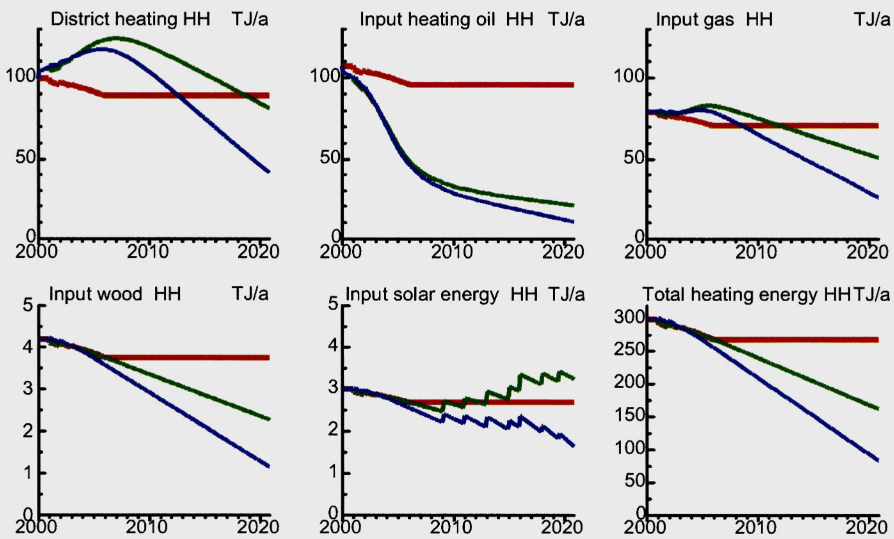

Fig.3. Energy flows for residential heating (TJ/a). Scenarios: BAU (in red), "Moderate" (in green) and "Extreme" (in blue). HH=households.

Both scenarios lead to a dramatic reduction in emissions from burning heating oil, such that the goal of eliminating CO_2 emissions from this source would almost be achieved both by moderate and extreme demand changes (Fig. 4, left). Regarding gas emissions, however, the second scenario is less efficient than the third: in the former case, the district per capita CO_2 emissions are reduced by only 0.06 t/a (status quo level is 0.26 t/a) as compared to 0.16t/a (Fig. 4, right) in the latter.

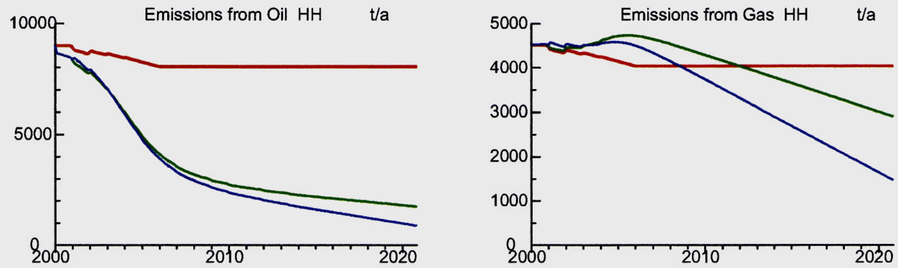

Fig. 4. Emissions from residential heating. (Scenarios colouring as in Fig.3)

Energy consumption for non-residential heating generally follows a similar pattern as for households, since the same fractions of energy sources are assumed (see Table 1). This is based on statistics of building use in Matthäus ([5], p.134): the majority (95,4%) of residential and non-residential uses share the same building, so that the means of energy supply may reasonably be assumed to be the same. The total heating energy demands of non-residential uses are however proportionally lower, due to the smaller proportion of users (number of local workers vs. district population).

In the electricity domain, a growth of power consumption is forecasted, followed by stabilisation to the status quo level in 2010 (Fig. 5). Furthermore, from our scenario assumptions (a return of per capita electricity consumption to the 1995 level), we obtain in 2020 an overall reduction of 20 TJ/a as compared to the present situation. This amount corresponds to the energy that is needed to fully cover the yearly demand of 500 one-family houses for heat and warm water (note that, by way of comparison, there are about 1000 (multi-family) residential buildings in Matthäus).

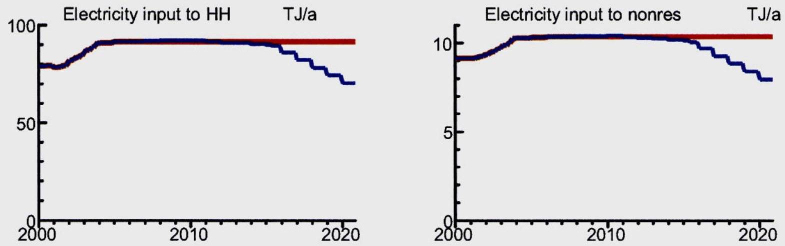

Fig. 5. District electricity consumption. BAU (in red), Electricity demand reduction (in blue).

DISCUSSION

A significant reduction in total heat energy use and associated CO_2 emissions can be achieved on two fronts: by reducing demand and changing the supply pattern. Two scenarios have been analysed and contrasted with the current status quo: a twofold or fourfold reduction of demand combined with the shift from heating oil towards more district heating and gas based heat along with a stepwise increase in solar thermal collector installations.

From the simulations carried out thus far we conclude that:

- The proposed demand side reductions prove to be quite effective, so that even increasing the proportion of one energy carrier (e.g. gas for heating) may still lead to a total reduction of associated input flow in the long term (2020 in this model). This evolution may lead to a short term (about 2010) peak but the demand constraint later leads to further supply side reductions.
- Both alternative scenarios lead to a strong reduction of CO_2 emissions from heating oil. Furthermore, emissions from gas also can be reduced by 20% to 60% depending upon the policies implemented.

Scenario calculations are useful for two main reasons. Firstly, they can help to determine the range of possible future states of a given urban site's metabolism. In addition, this can demonstrate that different scenarios may be concurrent, depending on the objective(s) or "target value(s)" that are set by city authorities as a development goal. Thus, as was shown here, the 'moderate' scenario would be sufficient to achieve the objective of practically ceasing oil consumption for heating. However, if sustainability objectives are formulated to minimise the CO_2 emissions, demand side reductions should be maximised; as with the more extreme scenario.

CONCLUSION AND OUTLOOK

In this paper the energy module of our model of district metabolism was presented. Clearly, the demonstrated scenarios are not exhaustive in terms of the whole range of possible energy futures of our district. However, they provide a dynamic outlook into the future and can be especially useful for solving "inverse problems" of urban energy management, i.e., scenarios can help to identify what changes are needed to meet certain goals/priorities for future energy flows and how the system can evolve towards them.

Although not presented in this paper, our MMFA model includes also a water module and a material & waste module; so that we have a rather comprehensive view of the flows of energy and matter through - or the metabolism of - our district and how these evolve with time. To make good use of this, future work will concentrate on the formulation and investigation of more comprehensive development strategies; considering also possible synergies with other districts or with the city as a whole. We will also consider the development of a comprehensive physical (thermodynamic) basis to assess the sustainability of proposed scenarios. The adjustment and application of this model to other urban districts, including those in rapidly developing regions with constantly increasing population and energy demand, is a potentially promising extension of this work.

ACKNOWLEDGEMENTS

The research presented in this paper has been carried out within the framework of the Swiss National Science Foundation Programme 54 from which the financial support is gratefully acknowledged. The authors also wish to thank Réne Etter (AUE Basel) and Christa Moll (StatA) for several fruitful discussions and for data support.

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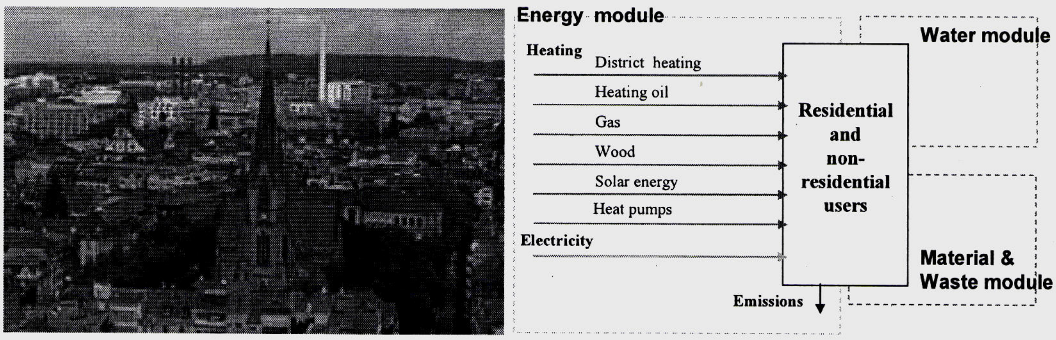

Figure 1: Left: The district of Matthäus, Basle (Source: www.statistik-bs.ch). Right: System analysis of district metabolism.

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The balance of heat and electricity demand and supply for the district serves as a basis for the mathematical description of the system. For each energy carrier, respectively, the input flow can be calculated as follows:

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where $I_i(t)$ is the i-th input flow (*TJ/a*), $P(t)$ is the district population, $P_u(t)$ is the use-specific (non)residential demand for heat/electricity ($MJ/C \cdot a$) and $f_i(t)$ is the fractional use of i-th energy source (district heating, oil, gas, wood and solar energy), $i = 1-5$ for residential and 6-10 for non-residential users respectively.

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Parameter function	Scenario	Development 2005-2020	Reference value source
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Spec. emissions c_i	all	const	84 *t/TJ* (oil), 57 *t/TJ* (gas)
Non-res. heat demand $P_{nrh}(t)$	BAU	const	23000 $MJ/w \cdot a$ *w=worker* [3]
	moderate	1,5-fold linear decrease	
Fractions of heat sources for non-res. uses $f_i(t), i = 6-10$	all	as for residential uses	[5, see in text]
Res. electricity demand $P_{re}(t)$	BAU	const	5820 $MJ/C \cdot a$ [2004, 2]
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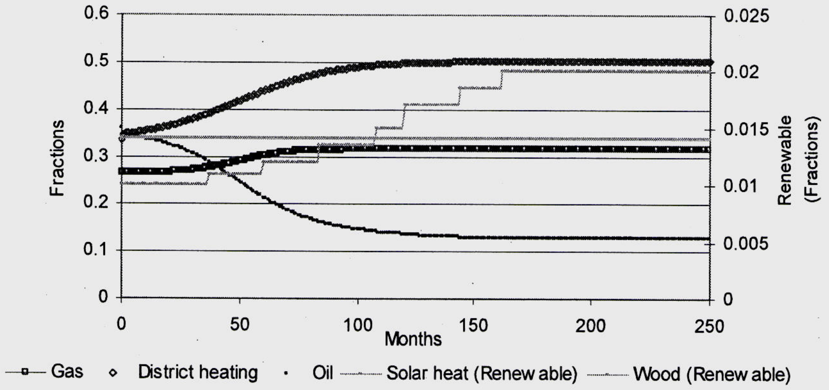

Fig. 2. Fractions of different heat energy carriers serving the district's households (2000-2020).

RESULTS

The evolution of the district's household heat consumption according to our three scenarios, for each considered energy source is shown in Fig. 3.

In both (alternative) scenarios, where we assume a deliberate fuel switch together with demand-side reduction, a strong reduction of energy consumption by 2020 is observed. Moreover, we observe that a decline of oil consumption for heating purposes to almost zero could be attained by 2020. Heating needs nevertheless remain large enough that locally converted solar energy may be progressively exploited (cf. "input solar energy" in the moderate scenario, Fig.3).

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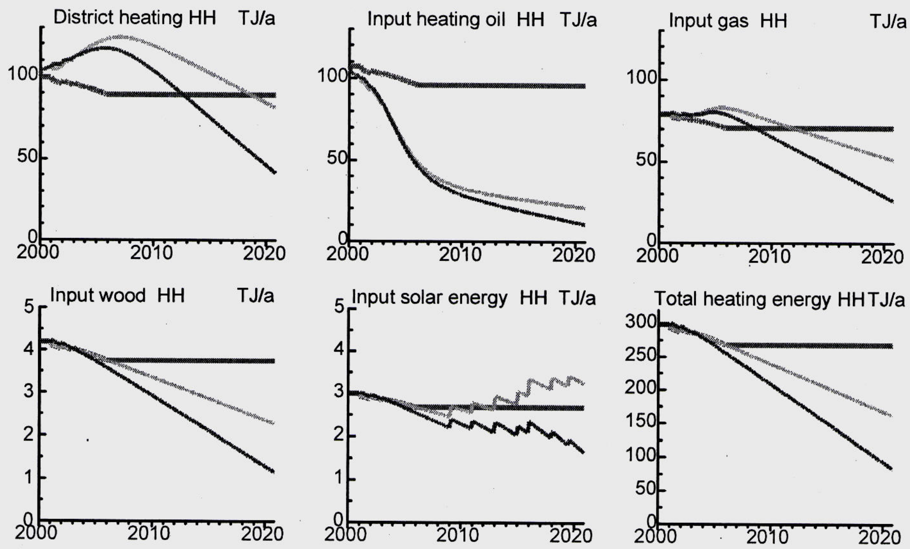
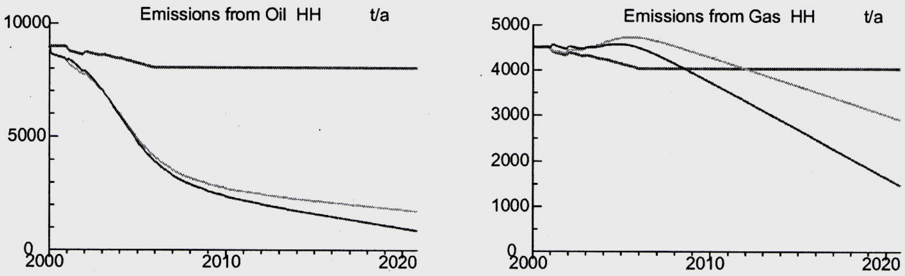


Fig.3. Energy flows for residential heating (TJ/a). Scenarios: BAU (in red), "Moderate" (in green) and "Extreme" (in blue). HH=households.

Both scenarios lead to a dramatic reduction in emissions from burning heating oil, such that the goal of eliminating CO_2 emissions from this source would almost be achieved both by moderate and extreme demand changes (Fig. 4, left). Regarding gas emissions, however, the second scenario is less efficient than the third: in the former case, the district per capita CO_2 emissions are reduced by only 0.06 t/a (status quo level is 0.26 t/a) as compared to 0.16t/a (Fig. 4, right) in the latter.



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Energy consumption for non-residential heating generally follows a similar pattern as for households, since the same fractions of energy sources are assumed (see Table 1). This is based on statistics of building use in Matthäus ([5], p.134): the majority (95,4%) of residential and non-residential uses share the same building, so that the means of energy supply may reasonably be assumed to be the same. The total heating energy demands of non-residential uses are however proportionally lower, due to the smaller proportion of users (number of local workers vs. district population).

In the electricity domain, a growth of power consumption is forecasted, followed by stabilisation to the status quo level in 2010 (Fig. 5). Furthermore, from our scenario assumptions (a return of per capita electricity consumption to the 1995 level), we obtain in 2020 an overall reduction of 20 TJ/a as compared to the present situation. This amount corresponds to the energy that is needed to fully cover the yearly demand of 500 one-family houses for heat and warm water (note that, by way of comparison, there are about 1000 (multi-family) residential buildings in Matthäus).

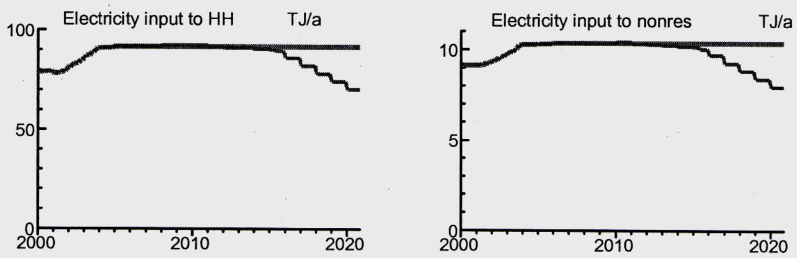

Fig. 5. District electricity consumption. BAU (in red), Electricity demand reduction (in blue).

DISCUSSION

A significant reduction in total heat energy use and associated CO_2 emissions can be achieved on two fronts: by reducing demand and changing the supply pattern. Two scenarios have been analysed and contrasted with the current status quo: a twofold or fourfold reduction of demand combined with the shift from heating oil towards more district heating and gas based heat along with a stepwise increase in solar thermal collector installations.

From the simulations carried out thus far we conclude that:

- The proposed demand side reductions prove to be quite effective, so that even increasing the proportion of one energy carrier (e.g. gas for heating) may still lead to a total reduction of associated input flow in the long term (2020 in this model). This evolution may lead to a short term (about 2010) peak but the demand constraint later leads to further supply side reductions.
- Both alternative scenarios lead to a strong reduction of CO_2 emissions from heating oil. Furthermore, emissions from gas also can be reduced by 20% to 60% depending upon the policies implemented.

Scenario calculations are useful for two main reasons. Firstly, they can help to determine the range of possible future states of a given urban site's metabolism. In addition, this can demonstrate that different scenarios may be concurrent, depending on the objective(s) or "target value(s)" that are set by city authorities as a development goal. Thus, as was shown here, the 'moderate' scenario would be sufficient to achieve the objective of practically ceasing oil consumption for heating. However, if sustainability objectives are formulated to minimise the CO_2 emissions, demand side reductions should be maximised; as with the more extreme scenario.

CONCLUSION AND OUTLOOK

In this paper the energy module of our model of district metabolism was presented. Clearly, the demonstrated scenarios are not exhaustive in terms of the whole range of possible energy futures of our district. However, they provide a dynamic outlook into the future and can be especially useful for solving "inverse problems" of urban energy management, i.e., scenarios can help to identify what changes are needed to meet certain goals/priorities for future energy flows and how the system can evolve towards them.

Although not presented in this paper, our MMFA model includes also a water module and a material & waste module; so that we have a rather comprehensive view of the flows of energy and matter through - or the metabolism of - our district and how these evolve with time. To make good use of this, future work will concentrate on the formulation and investigation of more comprehensive development strategies; considering also possible synergies with other districts or with the city as a whole. We will also consider the development of a comprehensive physical (thermodynamic) basis to assess the sustainability of proposed scenarios. The adjustment and application of this model to other urban districts, including those in rapidly developing regions with constantly increasing population and energy demand, is a potentially promising extension of this work.

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