THE ROLE OF HEAT PUMPS IN MULTI-ENERGY SYSTEMS IN CITY QUARTERS

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ABSTRACT

This paper uses a multi-energy system model based on mixed integer programming to analyse the effect of different flow temperatures and regulatory conditions on the utilisation of heat pumps in the heat supply of residential buildings. The analysis shows that the best option to promote heat pumps as an efficient technology for renewable-based heating is to reduce flow temperatures of heating systems rather than subsidising the electricity consumption.

1 INTRODUCTION

While the share of renewable energy is rising in the electricity sector, the transition of the heat sector towards a sustainable supply is falling short. As the building sector accounts for almost 40% of Europe's final energy consumption [1], additional efforts are necessary to increase the share of renewable energy in heat applications in order to meet the European climate targets.
Due to the increasing market share of modern conversion technologies like co-generation, heat pumps and photovoltaics, the different energy carriers become increasingly linked. At the same time, they become more exchangeable and thus optimizable in order to obtain cost and energy efficient solutions. Hence, current approaches for urban energy system design incorporate a multi-energy perspective [2–4]. This comprises the simultaneous consideration of the different energy carriers electricity, heat and natural gas.
Heat pumps are one key technology within sustainable energy systems as they allow substituting fossil fuels by electricity. However, in the current German regulatory framework the electricity price - which consists to one third of levies for renewable generation (EEG levy, see Table 4) – and technical constraints are the main obstacles for a higher market share of heat pumps. This paper discusses different scenarios for technical and regulatory conditions and their effect on the economic efficiency of heat pumps compared to alternative supply options, e.g. gas or biofuel boilers, solar thermal generators or the use of district heating (DH).
For this assessment a multi-energy optimization approach for the energy supply within city quarters is used. The focus is set on private households in family homes and apartment buildings.

2 OPTIMISATION MODEL

For the multi-energy modelling a mixed-integer linear optimisation approach is used. It determines the cost-effective set of conversion units for the heat and electricity supply for an assessment period of 20 years. The model describes the combined investment and operation problem and determines the optimal set of conversion units as well as the layout of an optional DH network. The work presented in this paper is based on an extension of the approach described in [5, 6].
The objective function of the resulting optimisation problem is formulated as follows:

$$\min \sum_{h=1}^{H} \left[\left(\sum_{K} C_{h,k}^{invest} \right) + C_h^{fix} + C_h^{el} + C_h^{th} - R_h \right] + C_{dh}^{invest}$$

with

h, H	Index of houses
k, K	Index of technologies
$C_{k/dh}^{invest}$	Investment costs for conversion technologies and district heating
C_h^{fix}	Fixed costs for each house (e. g. basic fees)
$C_h^{el/th}$	Generation costs for electricity/heat
R	Revenues from feed-in and subsidies

Heat and power supply

The optimisation approach comprises photovoltaic (PV) and combined heat and power (CHP) units for electricity generation. Heat can be generated by gas boilers, electrical heat pumps, wood pellet and wood chip boilers and solar thermal generators. In addition, thermal storages and battery systems are included. Renovation measures for increasing the energy efficiency of the buildings are included by comparing renovation scenarios. One or more optional district heating networks allow heat exchange between the heating plant and the objects connected.
Electricity generated locally can either be used within the building or it can be fed into the grid. In order to assess the effects of self-consumption of PV electricity the model's temporal resolution is set to 1 hour.

Modelling of heat pumps

The current approach models two types of electrical heat pumps: Air-source heat pumps (AHP) that use ambient air as an energy source and ground-source heat pumps (GHP) using a collector in the ground as their heat source. Both types are connected to a water-based central heating system.
The energy efficiency ratio EER of heat pumps is the quotient of the integrals of the generated heat g_{hp}^{th} and the required electrical power p^{el}:

$$EER = \frac{\int g_{hp}^{th}(t)dt}{\int p^{el}(t)dt}$$

Whereas the EER gives an indication of the overall efficiency by considering a whole year, the model uses the time-dependent coefficient of performance $COP(t)$. The COP is mainly dependent on the temperature lift between the variable temperature of the heat source ϑ_{source} and the flow temperature ϑ_F required by the heating system. If the domestic hot water (DHW) is supplied by central heating, its temperature level ϑ_{dhw} has to be considered as well. As the ϑ_{source} is not constant, it has to be weighed with the heat demand d^{th} and d^{dhw}. Based on a regression analysis of field test data from [7], the relationship equation has been determined as

$$COP(t) = \frac{g_{hp}^{th}(t)}{p^{el}(t)} = c_1 e^{-c_2\left(\frac{d^{th}(t)\vartheta_F + d^{dhw}(t)\vartheta_{dhw}}{d^{th}(t)+d^{dhw}(t)} - \vartheta_{source}(t)\right)}$$

with estimated parameters c_1 and c_2 given in Table 1.

	c_1	c_2
Air-source heat pump	4,9082	-0,014
Ground-source heat pump	14,411	0,042

Table 1: Parameters of heat pumps

The resulting EER and COP for the two types of heat pumps are given in Table 2 for two different flow temperatures.

	AHP		GHP	
Flow temperature in °C	35	55	35	55
EER	4,6	2,5	3,2	2,0
min COP	4,1	1,9	2,5	1,8
max COP	5,8	3,1	4,0	2,7

Table 2: Resulting efficiencies for heat pumps

Individual optimisation

If no district heating networks are considered, there is no coupling between the objects in one district. Therefore, each object can be optimised separately. As input data, individual time series of electrical and thermal demand are used describing one year. These are generated based on the objects' data like construction year, living space or number of inhabitants. Generation profiles for PV and solar thermal are based on TRY time series [8] and adjusted to the specific conditions of the object.

The results contain the net present value of costs (taking into account investment, fuel and operating costs) for heat and electricity supply for the assessment period. Furthermore, the optimal solution includes a complete set of investment decisions for each building indicating type and rating of each technology.

Optimisation including local heat networks

The optimum for each single building is used as the starting and reference solution for the optimisation of a local heat network. The iterative approach as described in [5] decouples the network design from the investment decision regarding conversion technologies and has been proved as scalable to city districts with 150 objects. It uses graph theory to generate networks as a minimal span tree. The solution may contain one or more networks. In each network one object is clearly defined to house the central heat station which can contain one or more different conversion technologies (e. g. CHP unit and peak boiler).

3 CASE STUDY

The developed approach is applied to the exemplary city quarter shown in Figure 1. The quarter represents a typical urban area of a small German town and is analysed using synthetically generated data. Temperature and solar irradiation data are derived from TRY-region 12 [8]. Further details of the quarter are given in Table 3.

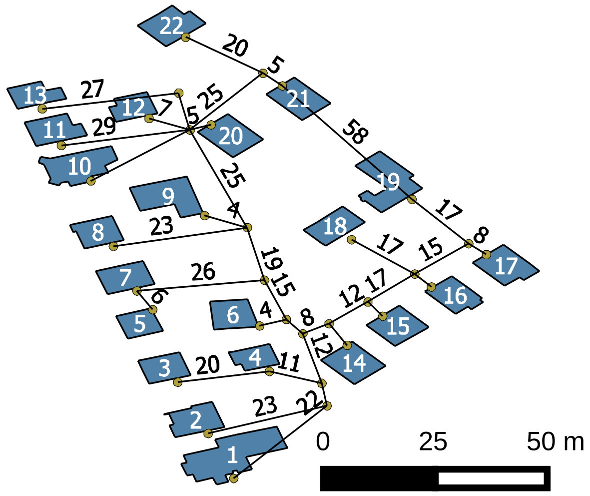

Figure 1: City quarter and possible DH routings

Single-family houses	12
Multi-family houses	10
Residential units	39
Inhabitants	79
Electrical demand in MWh/a	112
Thermal demand in MWh/a	543

Table 3: Characteristic values for the case study

In order to assess the impact of different regulatory frameworks for heat pumps, the district is analysed with two different flow temperatures of 35 °C and 55 °C respectively. Domestic hot water is not supplied by central heating.

Regulatory framework and input data

In the reference scenario, the current German regulatory framework is applied. In consequence, locally generated electricity is either used within the building or fed into the grid but not used within the district. Energy prices relevant for this paper are given in Table 4.

The full EEG levy is included in the energy prices and has to be paid for electricity purchased from the grid. However, electricity used for heating purposes profits from reduced grid fees. Self-consumption of electricity is exempted from all fees.

	Basic fee €/a	Energy price ct/kWh
Grid electricity	86,86	24,82
Grid electricity for heating	86,86	18,50
EEG levy	-	6,17
Natural gas	71,40	5,75
Wood chips	-	3,21
PV Feed-in tariff	-	12,31

Table 4: Key economic data as input for optimisation

The optimal investment results calculated by the model are used for an holistic assessment based on LCA data from [9]. The data relevant for this paper is given in Table 5. Note that the operation of heat pumps causes an environmental impact both by electricity generation and leakage of refrigerants.

	GWP / g CO_{2eq}/kWh	Dust / mg/kWh
Grid electricity	529	36
Gas Boiler	247	7
Wood chip boiler	26	169
Heat pump	19	0
PV System	63	34

Table 5: Key data for ecological assessment

Scenarios

The analysed scenarios are summarised in Table 6. For all 4 scenarios, the optimal solutions with and without DH networks are determined. Whereas low ϑ_F are typical for new buildings, they can also be set in existing objects after applying energetic renovation measures [10].

	$\vartheta_F = 35\,°C$	$\vartheta_F = 55\,°C$
Full EEG levy	F35	F55
No EEG levy	F35nE	F55nE

Table 6: Scenario definition

4 RESULTS AND DISCUSSION

Individual optimisation

At first, the results for the scenarios without DH are analysed. In the scenarios F35 and F55, the flow temperature and the heat pumps' resulting EER are the dominating factors for choosing the heating technology.
With respect to solar generation, heat pumps allow the economic operation of additional PV systems due to increased self-consumption. In consequence, the installed capacity of PV is increased by 30%. The operation of heat pumps implies the reduction of greenhouse gas (GHG) emissions by 40% compared to the supply by gas condensing boilers. At the same time, the overall costs are lower in the scenario with $\vartheta_F = 35\,°C$.

Scenario (no DH)	F35	F55	F35nE	F55nE
Gas boilers	3	22	0	11
Heat pumps	19	0	22	11
PV systems	15	11	11	11
PV capacity / kW_p	67,5	51,9	53,8	51,9
PV self-consumption / MWh/a	32,0	18,8	23,7	23,5
PV self-consumption / %	50,8	38,7	47,1	48,2
GWP electricity/ g CO_{2eq}/kWh_{el}	458	452	483	460
GWP heat/ g CO_{2eq}/kWh_{th}	148	247	125	241
Total costs / Mio. €	1,46	1,53	1,33	1,52

Table 7: Key results, Scenarios without DH network

When changing the regulatory framework by exempting the heat pumps' electricity from the EEG levy, the positive ecological benefit of heat pumps vanishes partly. Although not working at high EER, half of the buildings are supplied by heat pumps as the most cost effective solution (F55nE). However, due to the reduced EER no reductions in GHG emissions can be achieved compared to scenario F55. In addition, PV feed-in tariffs are on a level similar to the purchase costs of electricity for heating purposes (12,33 ct/kwh). Hence, the benefit of PV self-consumption by heat pumps is eliminated and additional heat pumps do not lead to additional PV systems (F35nE, F55nE).

Optimisation with optional DH network

A district heating network driven by a central wood chip boiler is the economical optimum in scenarios F35, F55 and F55nE. In all three cases, some houses are either supplied individually by heat pumps or gas boilers. The network's structure for F55 is shown in Figure 2.

Scenario (with DH)	F35	F55	F35nE	F55nE
Objects with DH	17	18	0	19
Gas boilers	0	4	0	0
Heat pumps	5	0	22	3
Wood chip boilers	1	1	0	1
PV systems	12	11	11	12
GWP electricity / g CO_{2eq}/kWh_{el}	437	452	475	449
GWP heat / g CO_{2eq}/kWh_{th}	42	56	124	45
Total costs / Mio. €	1,34	1,38	1,38	1,36

Table 8: Key results, Scenarios with DH network

The utilisation of biomass leads to further reductions of costs and GHG emissions. However, the emissions of dust as locally effective pollution rise by a factor of 10 (see total annual emissions of the district's energy supply in Figure 3). Finally, the successful installation and operation of a DH network in an existing district is afflicted with uncertainties: it is dependent on the availability of biomass, high connection rates and the presence of an investor and operator of the network.

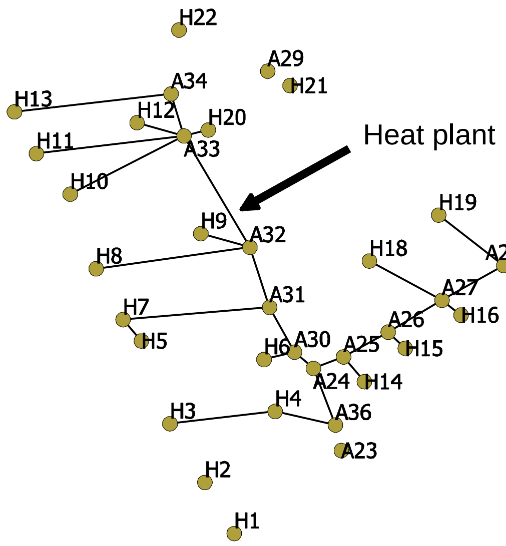

Figure 2: Local district heating network, scenario F55

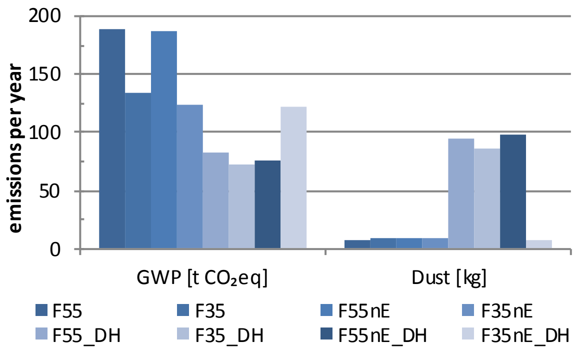

Figure 3: Emissions of the quarter's energy supply

5 CONCLUSION AND OUTLOOK

Heat pumps can play a key role for sustainable energy supply in dwellings. They allow higher shares of renewable energy sources in heating applications and enable reductions of greenhouse gas emissions. Suitable flow temperatures are required for their operation. As they lead to higher electricity consumption, they enable the economic operation of additional PV systems which are designed in order to maximise self-consumption.

However, if heat pumps profit from additional subsidies they may lose their ecological benefits. This is because they can be operated in objects in which other technologies should be preferred from a technical and ecological perspective.

With respect to a global optimum regarding economic and sustainable solutions, the reduction of flow temperatures is identified as an important driver rather than subsidising electricity for heat applications. Flow temperature reduction can be achieved by upgrading a building's energy performance.

Additional effort should be put in the analysis of the link between ecological benefits and costs. Therefore, it is planned to extend the optimisation approach to a multi-objective optimisation.

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